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# PROOF TESTING OF A CANDIDATE CATEGORY 3 SUPPRESSIVE SHIELD

by

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A prototype structure was designed, fabricated, and tested as a candidate suppressive shield for Category 3 applications. The tests indicate complete containment of secondary fragments from press/pelletizing equipment and blast pressure reductions in the range of 70 to 92% at external close-in locations. The shield did not successfully withstand the required proof test of 560 psi side-on blast overpressure at the wall, due to the ejection of three pieces of 10-gauge perforated steel from the outside layer of the vented panels becoming secondary fragments.

## PREFACE

The investigation described in this report was authorized under PA, A 4932, Project No. 5751264, "Advanced Technology for Suppressive Shielding of Hazardous Production and Supply Operations", and with the issuance of MIPRs B4075 and 81551176l1F4WS. The work was performed at the NASA National Space Technology Laboratories (NSTL) by the Edgewood Arsenal Resident Laboratory (EARL) through NASA-NSTL with the General Electric Company and Global Associates as support contractors. The experimental work was completed in October 1975.



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## 1.0 INTRODUCTION

1.1 Objective. The objective of this program was to design, fabricate and test a vented enclosure that would suppress fragmentation from detonations within a compress/pelletize operation and reduce the resultant blast pressure to a tolerable level. The shield was designed to withstand peak side-on blast pressures at the wall of 500 psi.

1.2 Authority. The investigation described in this report was authorized under PA, A 4932, Project No. 5751264, MIPRs B4075 and 8155117611F4WS. The work was performed by the Edgewood Arsenal Resident Laboratory (EARL) at the NASA National Space Technology Laboratories (NSTL) with support from the General Electric Company and Global Associates.

1.3 Background. In 1973 the basic criteria for a series of vented explosive containment structures called suppressive shields were defined in terms of seven major categories of potential applications. For generic Category 3, the primary hazard parameters against which protection is desired are:

- Side-on blast overpressures in the range from 200 to 500 psi at the interior walls of the enclosure, and
- Light to moderate secondary fragmentation.

Representative operations include small to medium caliber munition processing operations and munition component manufacturing.

A survey of the US Army ammunition plants was conducted during the third quarter of fiscal year 1974, resulting in selection of the compress/pelletizing operation in Area F at Lone Star Army Ammunition Plant as the primary category 3 candidate application. An explosive screening operation in the time fuse line at Iowa Army Ammunition Plant was chosen as a secondary application.

## 2.0 EXPERIMENTAL METHODS AND MATERIALS

2.1 Design and Fabrication. The design guidelines for the candidate Category 3 suppressive shield are as follows:

- The structure shall be designed to withstand the detonation of an explosive charge sufficient to generate 500 psi peak side-on overpressure at the walls of the enclosure.
- The structure shall contain all fragmentation from a 10-pound high explosive charge placed within simulated equipment representative of the primary candidate application.

- Side-on blast overpressure will be reduced by 80 percent at a distance of 29 feet from the charge.

- A door shall provide adequate personnel access for maintenance and allow clearance for moving the candidate equipment (Cherry-Burrell Model 270 Rotary Table Press) in or out.

- The design shall incorporate a structural framework to which are attached modular panel subassemblies. The framework shall have structural strength sufficient to withstand all loading requirements and shall be rigidly mounted on a reinforced concrete slab.

- Minor permanent deformation of the entire structure after one verification test shall be permitted provided structural integrity is maintained and functional characteristics are retained. Stresses caused by tests performed prior to the certification test shall not exceed allowable stresses specified by the American Institute of Steel Construction, Inc.

- The structure is required to replace the existing concrete cubicle for the press/pelletize operation in Area F at Lone Star Army Ammunition Plant (AAP). The approximate interior dimensions of the suppressive structure shall be 10 ft. x 10 ft. x 10 ft.

The original design approach utilized procedures that primarily rely upon quasi-static pressure loading of the structure (1). The design is similar to other previously developed suppressive shields (2, 3, 4) and consists of a rigid structural steel frame in which vented steel panels are inserted. The panels are held in place by wedges driven into ears attached to the frame. Photographs and design drawings of the structure as originally fabricated are shown in Appendix A.

An independent analysis of structural loading based on integral wall sections and yield strength of materials was performed during fabrication. This analysis indicated weaknesses with respect to shear at the intersections of the structural frame. Accordingly, modifications to the original design were performed prior to testing. The Phase I modifications to the structure as tested are shown in Appendix B.

## 2.2 Test Program

2.2.1 Test Description. A series of tests was performed within the completed structure using progressively larger quantities of explosive to evaluate the effectiveness of the Category 3 suppressive shield design, to provide empirical data on hazard parameter reduction by vented enclosures and to provide basic data on structural response of enclosures exposed to high explosive detonations. The experimental work was performed under Test Specification for Category 3 Suppressive shield (5) and consisted of four test series:

- Test A1 - 1.47 pounds of bare spherical 50/50 pentolite was detonated at a height of 57 inches in free-field for calibration of the instrumentation systems.

- Test A2 - 11.8 pounds of bare spherical 50/50 pentolite was detonated at a height of 57 inches in free-field for calibration of the instrumentation systems.

- Test A3 - 45.6 pounds of bare spherical 50/50 pentolite was detonated at a height of 57 inches in free field for calibration of the instrumentation systems.

- Test B1 - Five pounds of bare spherical 50/50 pentolite was detonated 57 inches above the floor in the geometric center of the structure to provide approximately 100 psi side-on blast pressure at the nearest wall (5.2 ft.).

- Test B2-X - 11.8 pounds of bare spherical 50/50 pentolite was detonated 57 inches above the floor in the geometric center of the structure at the position where the center of mass I-527 igniter mix powder would be located inside a 16-gauge stainless steel hopper, see figures 1, 2, and 3. This test setup provided approximately 200 psi side-on blast pressure at the walls and a fragment hazard similar to that expected from the Cherry-Burrell Model 270 rotary table press hopper in the candidate operation at Area F, Lone Star AAP. This test was repeated in the Phase II modified shield using an 11.6-lb. charge.

- Test B3-X - 57.2 pounds bare spherical 50/50 pentolite was detonated 57 inches above the floor in the geometric center of the structure to provide approximately 560 psi side-on blast pressure at the nearest wall. The charge weight of 57.2 pounds represent 125 percent of the design explosive weight (46 lbs.). The 125 percent overload is a requirement of the USAMC Safety Office for Safety Certification of suppressive shields. This test was repeated in the Phase II modified shield using a 59.9-lb. charge.

In each test the charge was suspended on the vertical centerline at a height of 57 inches and detonated with a J-2 blasting cap. Test series B3-X utilized approximately 4 grams of PETN as a booster in conjunction with the J-2 blasting cap. These tests were preceded by appropriate free-field detonations to provide comparable blast pressure data. Side-on blast pressures obtained in the free field test series "A" correlated within experimental error to Soroka's curve (6) and are shown in table 1.

2.2.2 Test Measurements. Measurements of internal and external blast pressure, internal quasi-static pressure and reflected pressure were made during all tests in the suppressive shield. Details of instrumentation are given in table 2 and a plan view of transducer placement for tests B1-1, B2-1 and B3-1 is shown in figure 4 with figure 5 displaying the plan view of transducer placement for tests B2-2 and B3-2.

Piezoelectric sensors were used to measure side-on blast pressure external to the shield. Susquehanna Instruments ST-7H transducers with integral ballistic probes were mounted in stands constructed of 2-inch iron pipe such that the probe was horizontal at charge height and oriented toward the direction of the charge. The transducer stands were staggered and offset to minimize reflection interferences.

Piezoelectric transducers were used to measure internal blast reflected pressure at the walls of the shield. Susquehanna Instruments ST-4 transducers were mounted flush with the interior structural frame within 1-1/2-inch-diameter cylindrical teflon blocks such that electrical and shock isolation from the structure was afforded. All of the

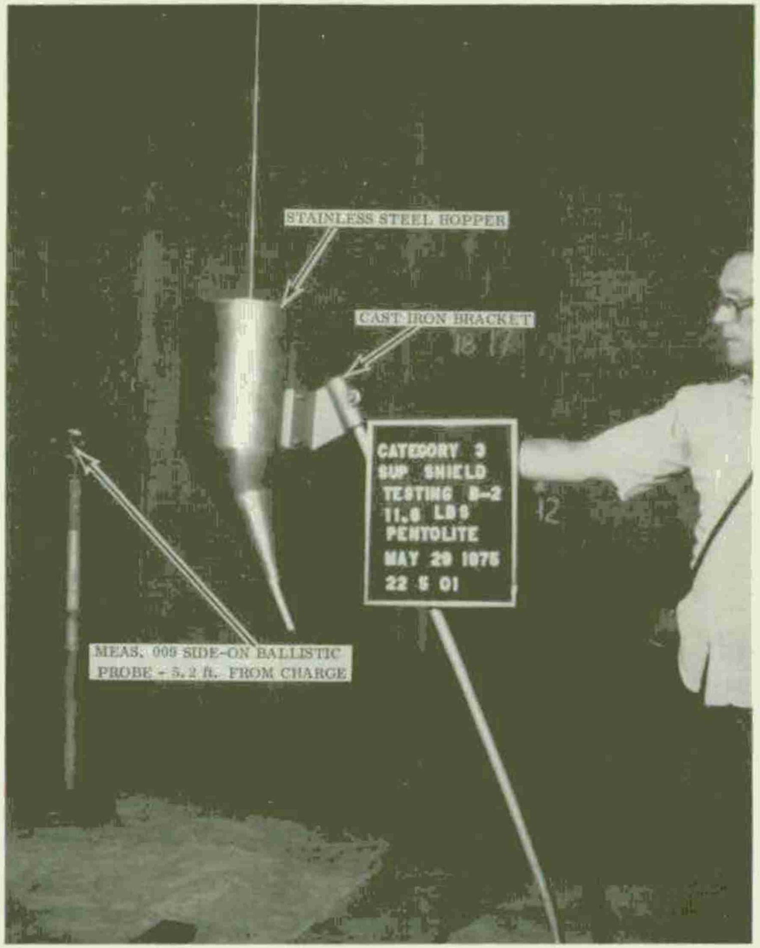



Figure 1. Category 3 Candidate Operation Test B2-1 Setup Showing the Primary Fragment Threat of the Hopper from Press-Pelletizing Operation at Lonestar Army Ammunition Plant

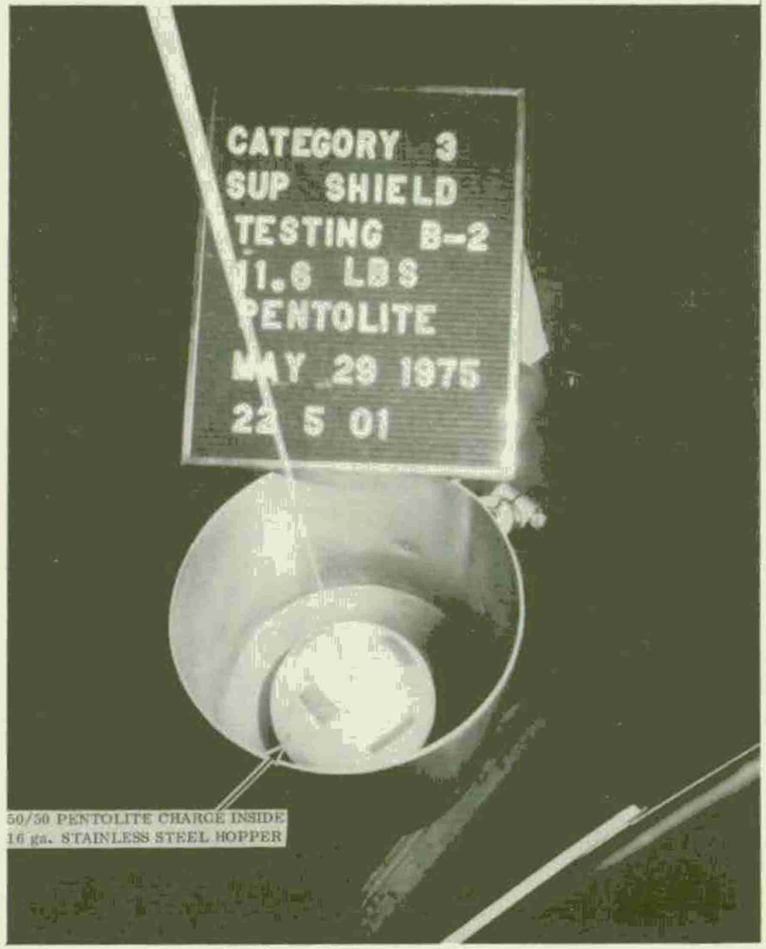



Figure 2. Category 3 Candidate Operation Test B2-1. Pentolite Charge Suspended in 16-Gauge Stainless Steel Hopper From Press-Pelletizing Operation at Lonestar Army Ammunication Plant.

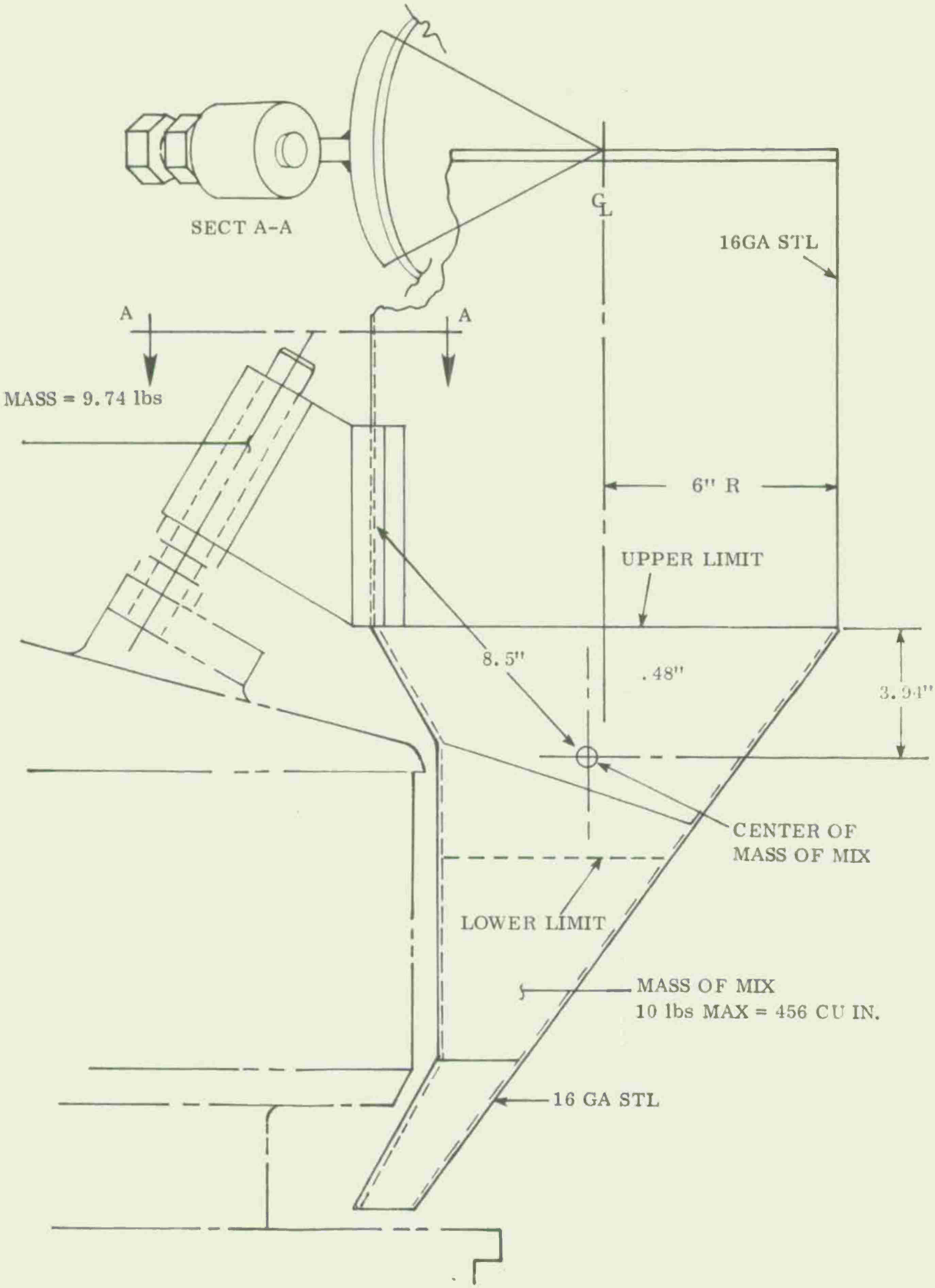



Figure 3. Configuration Details of Stainless Steel Hopper From Candidate Operation, Lonestar Army Ammunication Plant Used in Category 3 Tests B2

Table 1. Category 3 Suppressive Shield Tests A1-1, A1-2 and A1-3, Free Field Calibration of Side-on Blast Pressure Measurements

| Test No. | Charge Weight (lbs.) | Type of Transducer Mounting | Distance from Charge (Ft.) | Z (Ft. $W^{-1/3}$) | Pressure Side-on (psi) Soroka (6) | Pressure Side-on (psi) (Test) |
|---|---|---|---|---|---|---|
| A1-1 | 1.47 | Ballistic | 8.7 | 7.62 | 13.0 | 14.1 |
| | | | 8.7 | 7.62 | 13.0 | 13.1 |
| | | | 9.7 | 8.50 | 10.4 | 10.4 |
| | | | 10.5 | 9.20 | 8.8 | 9.3 |
| | | | 10.5 | 9.20 | 8.8 | 10.6 |
| A1-1 | 1.47 | | 10.5 | 9.20 | 8.8 | 10.0 |
| A2-1 | 11.8 | | 8.7 | 3.82 | 64. | 67.4 |
| | | | 8.7 | 3.82 | 64. | 61.7 |
| | | | 9.7 | 4.26 | 49. | 46.4 |
| | | | 14.0 | 6.15 | 20.8 | 16.7 |
| | | | 14.0 | 6.15 | 20.8 | xx |
| | | | 14.0 | 6.15 | 20.8 | 23.2 |
| | | | 19.0 | 8.34 | 10.8 | 11.7 |
| | | | 19.0 | 8.34 | 10.8 | 9.5 |
| A2-1 | 11.8 | | 19.0 | 8.34 | 10.8 | 7.1 |
| A3-1 | 45.6 | | 8.7 | 2.44 | 180. | 150. |
| | | | 8.7 | 2.44 | 180. | 113. |
| | | | 9.7 | 2.72 | 142. | 145. |
| | | | 14.0 | 3.92 | 60. | 57. |
| | | | 19.0 | 5.32 | 29. | 30.6 |
| | | | 19.0 | 5.32 | 29. | xx |
| | | | 23.0 | 6.44 | 18.8 | 12.3 |
| | | | 32.0 | 8.96 | 9.3 | 8.1 |
| | | | 32.0 | 8.96 | 9.3 | xx |
| A3-1 | 45.6 | Ballistic | 32.0 | 8.96 | 9.3 | xx |

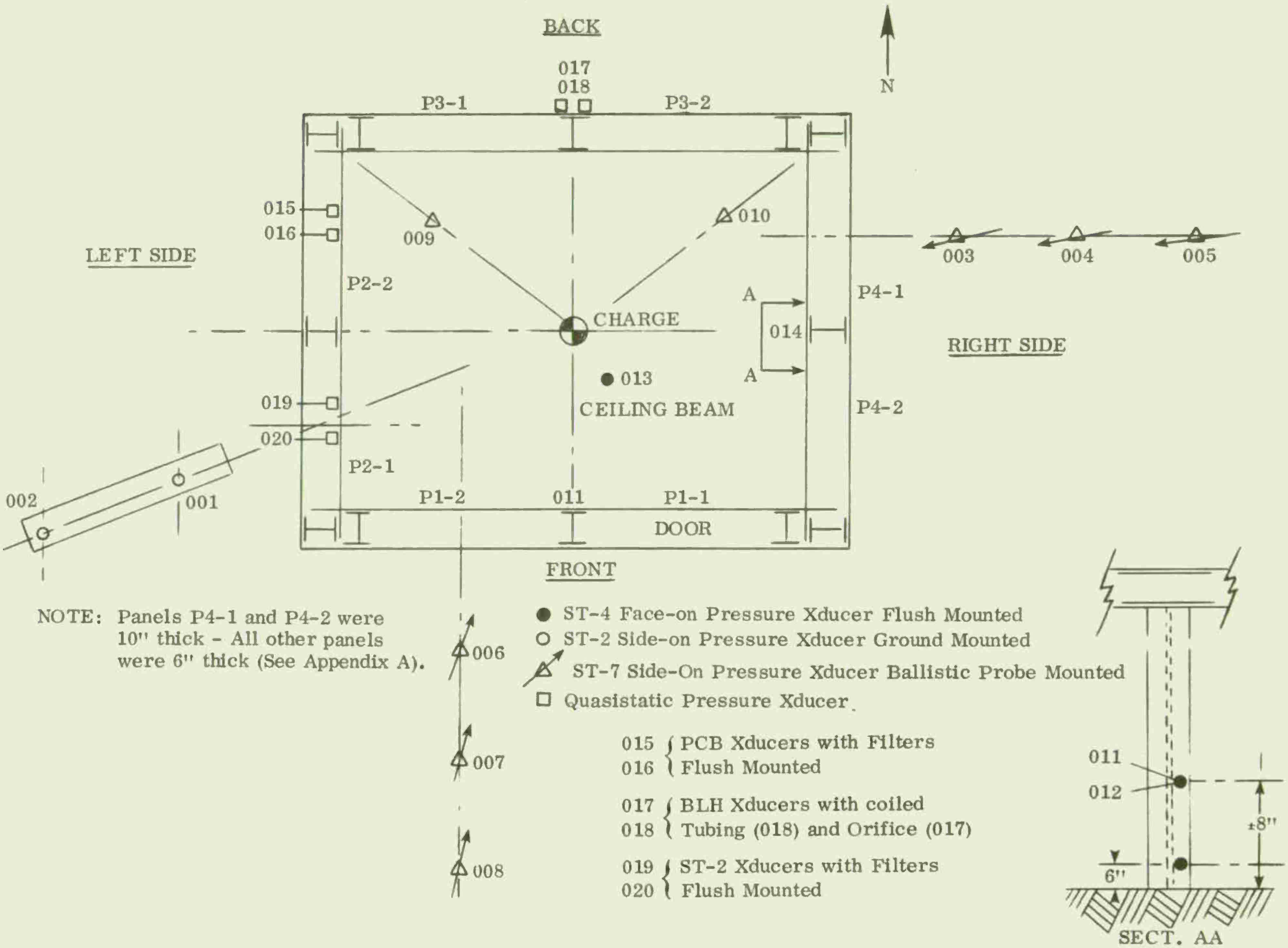
Table 2. Category 3 Suppressive Shield Explosive Containment Tests Instrumental Details

| Parameter | Transducer | Amplifier | Cable | Recorder | Installed Time Constant |
|---|---|---|---|---|---|
| Blast Pressure (side-on) | ST-7H (ballistic probe) | PCB 401A11 | 1100 ft. RG58 C/U | Biomation 610B Honeywell 96 | 10 sec. 200 msec. |
| Blast Pressure (side-on) | ST-2 Ground Mount | PCB 401A11 | 1100 ft. RG58 C/U | Biomation 610B Honeywell 96 | 10 sec. 200 msec. |
| Blast Pressure (Refl.) | ST-4 wall mount | PCB 402A02 | 1100 Ft. RG58 C/U Coax | Honeywell 96 | 200 msec |
| Quasi-static Pressure | PCB 101A02 in baffle mount | NEFF 109-6 | 1100 ft. RG58 C/U | Sangamo 4700 | 10 sec. |
| Quasi-static Pressure | ST-2 in baffle mount | NEFF 109-6 | 1100 ft. RG58 C/U Coax | Sangamo 4700 | 10 sec. |
| Static Pressure Test B1 | Allegheny Model 151-HAC-134 0 to 50 psis | NEFF 109-6 | 1100 ft. RG58 C/U Coax | Sangamo 4700 | Not applicable |
| Static Pressure Test B2 | MB electronics Model 151-HAC-134 0-200 psis | NEFF 109-6 | 1100 ft. RG58 C/U Coax | Sangamo 4700 | Not applicable |
| Static Pressure Test B3 | MC electronics Model 151-HAC-134 0-200 psis | NEFF 109-6 | 1100 ft. RG58 C/U Coax | Sangamo 4700 | Not applicable |

face-on measurements were made at a height of 48 inches from the floor due to interference of the panel wedges and bars at the charge height of 57 inches. Susquehanna Instruments ST-2 piezoelectric transducers were used to measure blast pressure external to the shield at ground level. The ST-2 transducers were mounted externally within teflon inserts in a 12 x 50 channel, similar to the arrays described in earlier work (7).

2.2.2.1 Tests B1-1, B2-1 and B3-1

Two PCB 101-A02 and two ST-2 transducers were used to measure internal quasi-static pressure and were mounted at the interior wall surfaces in isolation chambers similar to that described by Schumacher (7). Two strain gauge type static pressure transducers




NOTE: Panels P4-1 and P4-2 were 10" thick - All other panels were 6" thick (See Appendix A).

● ST-4 Face-on Pressure Xducer Flush Mounted
○ ST-2 Side-on Pressure Xducer Ground Mounted
ST-7 Side-On Pressure Xducer Ballistic Probe Mounted
□ Quasistatic Pressure Xducer

015, 016 — PCB Xducers with Filters Flush Mounted
017, 018 — BLH Xducers with coiled Tubing (018) and Orifice (017)
019, 020 — ST-2 Xducers with Filters Flush Mounted

Figure 4. Schematic Diagram of Category 3 Test Instrumentation Arrangement

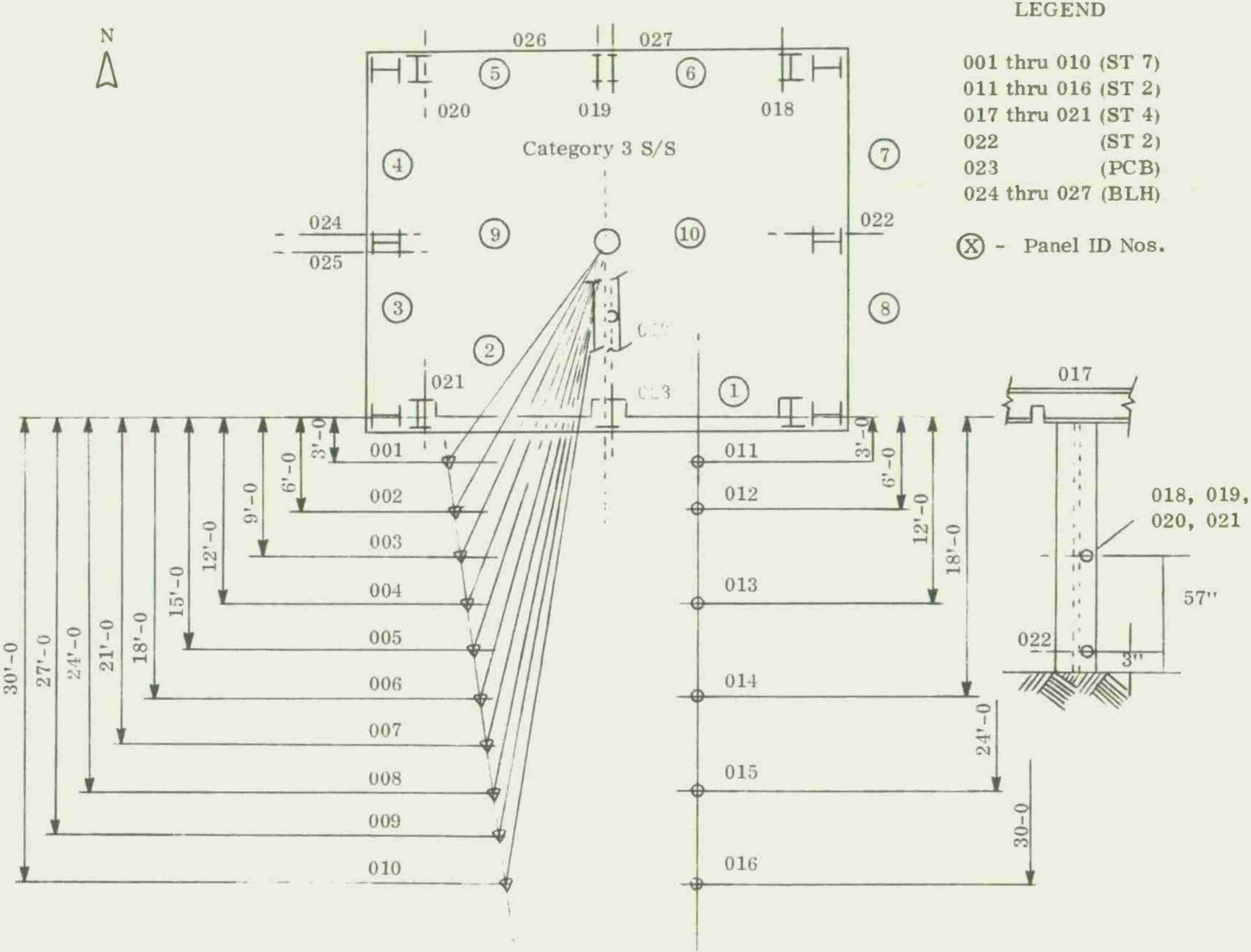



Figure 5. Category 3 Transducer Locations Tests B2-2 and B3-2

were also used to measure the quasi-static pressure. One such transducer was isolated from the structure's interior by a coil of 1/4-inch steel tubing approximately 43 inches long.

The other static pressure gauge was connected to a 14-inch length of 1/4-inch stainless steel tubing with a 0.100-inch orifice at the transducer for test B1 and a 0.070-inch orifice for the remaining tests. The tube and orifice aid in mechanical filtration of the high frequency blast and reflected pressure signals from the slower varying quasi-static pressure traces.

In addition, the structure was instrumented with approximately 40 BLH weldable strain gauges and two Southwest Research Institute designed wall displacement gauges; data and analysis of these measurements will be provided in a subsequent report (8). External motion picture coverage of the tests was provided by two Hycam Model 41.004 cameras that were preset to 800 frames per second due to limited light. A 24-frame per second Mitchell camera provided real time documentary film coverage. During Test B3-1, an additional Mitchell camera operating at 500 frames per second was placed at a distance of approximately 560 feet from the structure to provide wide angle documentary coverage.

#### 2.2.2.2 Tests B2-2 and B3-2

The number of PCB 101-A02 and ST-2 transducers was reduced to one each since low resolution data from these sources had been observed in previous tests. The number of strain gauge type pressure transducers was increased from two to four. The four MBE Model 151-HAC-134 transducers were connected to the shield in the following manner:

No. 1 - A 14-inch length of 1/4-inch stainless steel tubing with a 0.070-inch-diameter orifice at the transducer inlet.

No. 2 - A 14-inch length of 1/4-inch stainless steel tubing with a 0.100-inch diameter orifice at the transducer inlet.

No. 3 - A 14-inch length of 1/4-inch stainless steel tubing without any orifice.

No. 4 - A 14-inch length of 1/4-inch stainless steel tubing attached to a 43-inch coil of 1/4-inch stainless steel tubing and attached to the transducer.

No strain data was acquired during these tests because of fragment damage and yield of frame members beyond the range of the welded strain gauges from previous tests B2-1 and B3-1 and the extensive modifications to the shield.

External motion picture coverage was provided by three Hycam Model 41.004 cameras that were operated up to 8000 frames per second. A 70-mm Hulcher camera operating at 20 frames per second was used for documentary coverage along with a 500 frames per second Mitchell located on the revetment 560 feet from the structure.

## 3.0 TEST PREPARATIONS

Prior to the commencement of the planned series of tests of the Category 3 suppressive shield, a one pound charge of C-4 explosive was detonated inside the shield to remove rust and scale to enhance the high speed photography as had become standard practice for other

shields (Category 5, 81mm) previously tested at NSTL.

Upon examination of the shield after the detonation it was discovered that the outer perforated plates of the panels had bowed out approximately 2 to 2-1/2 inches and had also bent inward the legs of the angles that make up the panel frames in the plane of the perforated plates.

An extensive design analysis was performed by a structural engineering consultant and the category 3 suppressive shield design was modified according to the findings of the consultant. Appendix A of this report shows the initial design of the suppressive shield when the one pound charge of C-4 was detonated. Appendix B shows the modifications recommended by the consultant and approved by the Corps of Engineers and is the configuration of the shield "as tested" for tests B1-1, B2-1 and B3-1 and hereinafter referred to as Phase I modifications.

The primary Phase I modifications were: 1) The welding of gusset plates between the flanges of the roof I-beams to permit the entire I-beam to experience the loading rather than just one flange; 2) Torsion plates were welded at the intersection of the two outer roof beams and the shield's two sides to strengthen these joints; 3) Welding on the inside of large gussets to the side columns and roof beam intersection to strengthen the roof beam in shear loading; and 4) Strengthen the panels of the shield by welding a 1/2-inch by 6-inch stiffner on the outer sides of the panel frame to resist the inward forces caused by the outer bending of the perforated plates. In the case of the 3X panels, a 1/2-inch x 8-1/4-inch stiffner was welded to the outer sides of the panel frame. No change was made to the outer layer of perforated steel plate in each of the panels or its attachment method to the panel frame. Calculations performed by Southwest Research Institute indicated the outer layer of perforated steel plate would bow out approximately 11 inches to develop the full membrane strength of this member before failure even though bending was observed at the attachment weld to the panel frame.

## 4.0 TEST RESULTS

The initial test plan for the Category 3 suppressive shield called for one test in each of the BX-1 series. Tests B1-1 and B2-1 were completed with expected satisfactory results. However, test B3-1 resulted in unexpected failure of the shield in three of the ten panels. New panels were then designed and installed in the shield and modifications were made to the frame. Test series B2 and B3 were then rerun to complete the proof testing and to attempt final qualification of category 3 suppressive shield.

4.1 Structural Damage. Test B3-1 caused a catastrophic failure of 3 of the 10 panels (9 panels plus 1 door panel). Failure occurred in the panel frames at the corners of the structural frame (see figures 6 and 7). This permitted the panels to exit the structure with a minimum deformation of the opposite side of the panel frame and by partial shear and bending of the top and bottom portions of the panel frame. Panel No. P2-1 was found approximately 290 feet to the west from the shield where its forward motion was arrested by a 10-inch diameter oak tree. The adjacent panel, No. P2-2, was 105 feet to the west and Panel No. P3-2, 62 feet north (see figure 8). The outer layer of perforated steel plate of Panel 4-2 (see figure 6) failed by ripping in the center of the panel indicating the membrane strength of this member had been exceeded. Figure 9 shows the relative movement of the structure in relation to the ground plan.

Following Test B3-1, the main structural frame showed damage in that the two gusset plates (1-inch thick) which connected the roof beam to the wall columns were cracked diagonally toward the roof-wall intersection. These cracks extended into roof beam-to-wall column welds (see figure 10).

The category 3 suppressive shield was again subjected to a design analysis review with the assistance of the Corps of Engineers (CoE) and Southwest Research Institute (SwRI) and modification and repairs effected to the shield. The Phase II modifications to the shield as a result of the analyses are shown in Appendix C, Category 3 Suppressive Shield Phase II Modifications. The primary changes were:

1. The addition of 1/2" x 6" steel plates across the top strap on the roof and on top of the two intersecting wide flange I-beams in the concrete floor.

2. A new gusset designed and installed at the column to roof beam. (Figure 11)

New panels were designed and installed. The new panels had frames made of 6" x 4" x 5/8" thick angles, compared to 6" x 4" x 3/8" thick angles for the initial designs. The slight line of sight through the panels was corrected by changing the spacing of the fragmentation layer angles to 1-1/2 inches vs 1-3/4 inches. This provided 10 additional angles to the fragmentation layer of the panel.

The gap between the structural frame of the suppressive shield and the panel frames was reduced to 1/8 inch. To further support the panel against blast loading and fragments a 1-1/2 x 2 inch steel bar was welded to the main structural frame around the panel openings. No change was made to the attachment method of the various venting members to the panel frames since the ripping of the perforated steel plate on Panel 4-1 from test B3-1 did not generate secondary fragments. In fact, complete structural failure of this suppressive shield would have been an acceptable test guideline if no primary or secondary fragment escaped the shield; <u>no secondary fragments were generated externally and blast pressure was reduced by 80 percent outside the shield.</u>

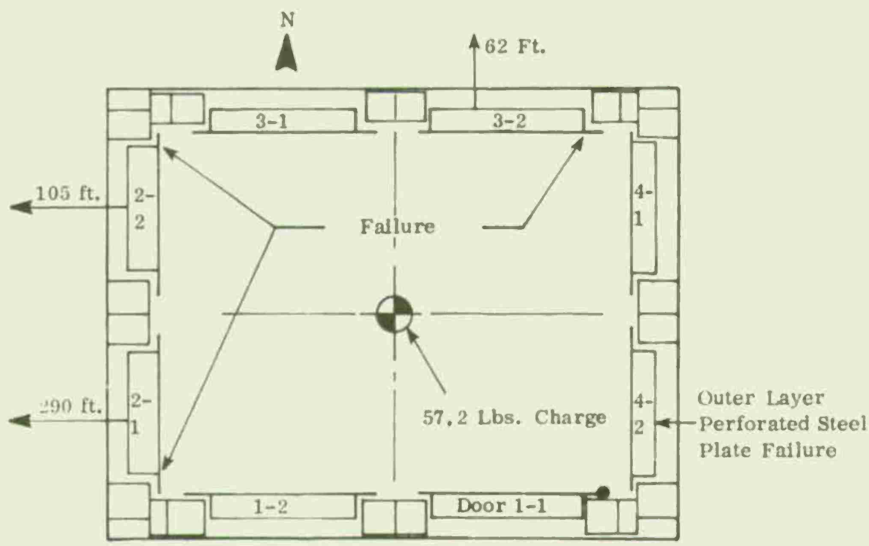



Figure 6. Category 3 Test B3-1 Proof Pressure Test - Ejected Panel Locations and Directions Diagram

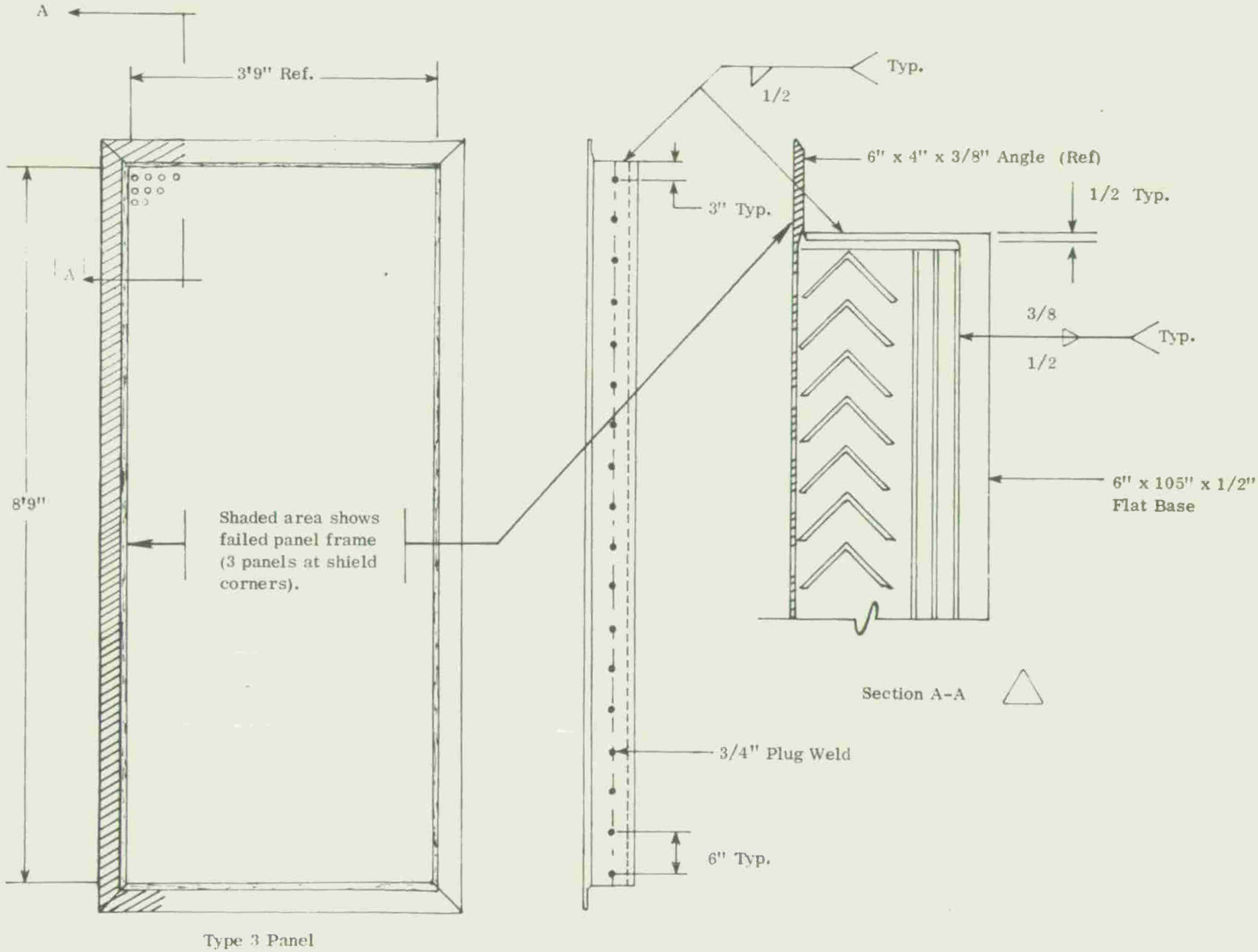



Figure 7. Category 3 Test B3-1 Proof Pressure Test - Diagram of Panel Frame Failure


Figure 8. Category 3 Test B3-1 Proof Pressure Test - Ejected Panels Location and Direction


Figure 9. Category 3 Test B3-1 Proof Pressure Test - Relative Horizontal Motion of Structure


Figure 10. Category 3 Test B3-1 Proof Pressure Test - Damaged Gusset in Wall Column to Roof Beam Intersection

Figure 11. Category 3 Test B3-2 Proof Pressure Test - New Phase II Design Gusset Installation

Test B2-2 was accomplished with the expected satisfactory results. However, test B3-2 proof test with 59.9 lbs. pentolite explosive caused large sections of the outer layer of perforated plate on three panels to separate from the shield. Two of the three pieces of perforated plate were found about 30-50 feet from the shield on opposite corners. The third piece was found approximately 386 feet to the southeast of the shield. With only one exception (panel no. 3), nearly all the perforated plates were ripped and separated at the corners of the shield, in the same general locations where the original panels suffered failure. The failure of the one perforated plate in test B3-1 occurred at the center of the panel and no separation was noted.

Damage to the perforated plates from test B3-2 demonstrated that the perforated plates failed from the blast loading and did not develop the full membrane strength by which panels of this type have previously been designed. Figures 12 through 16 illustrate the structural damage of the shield from test B3-2. No apparent damage occurred to the structural frame. Figure 17 shows the explosive set-up for test B3-1 which was identical to that for test B3-2 except for the 2-lb. smaller charge.

4.2 <u>Pressure Measurements</u>. The panel configuration for tests B1-1, B2-1 and B3-1 used the configuration shown in appendices A and B. The vent areas were 19 percent for the 4 layers of perforated plates and 89 percent for the fragmentation layer of angles. The effective venting coefficient, $\alpha$ eff, calculated by

$$\frac{1}{\alpha_{eff}} = \frac{1}{\alpha_1} + - - + \frac{1}{\alpha_N};$$

$$\frac{1}{\alpha_{eff}} = \frac{1}{.193} + \frac{1}{.891} + \frac{1}{.193} + \frac{1}{.193} + \frac{1}{.193}$$

$$\alpha_{eff} = .046$$

The new panels were installed for tests B2-2 and B3-2 and were configured as follows:

1st layer 20.2% open 10 ga. perforated plate

2nd layer 87% open, fragmentation layer of angles

3rd layer 16.8% open, 10 ga. perforated plate

4th layer 16.8% open, 10 ga. perforated plate

5th layer 18.4% open, 10 ga. perforated plate

The $\alpha$ eff for the new panel configuration is:

$$\frac{1}{\alpha_{eff}} = \frac{1}{.202} + \frac{1}{.873} + \frac{1}{.168} + \frac{1}{.168} + \frac{1}{.184}$$

$$\alpha_{eff} = .043$$

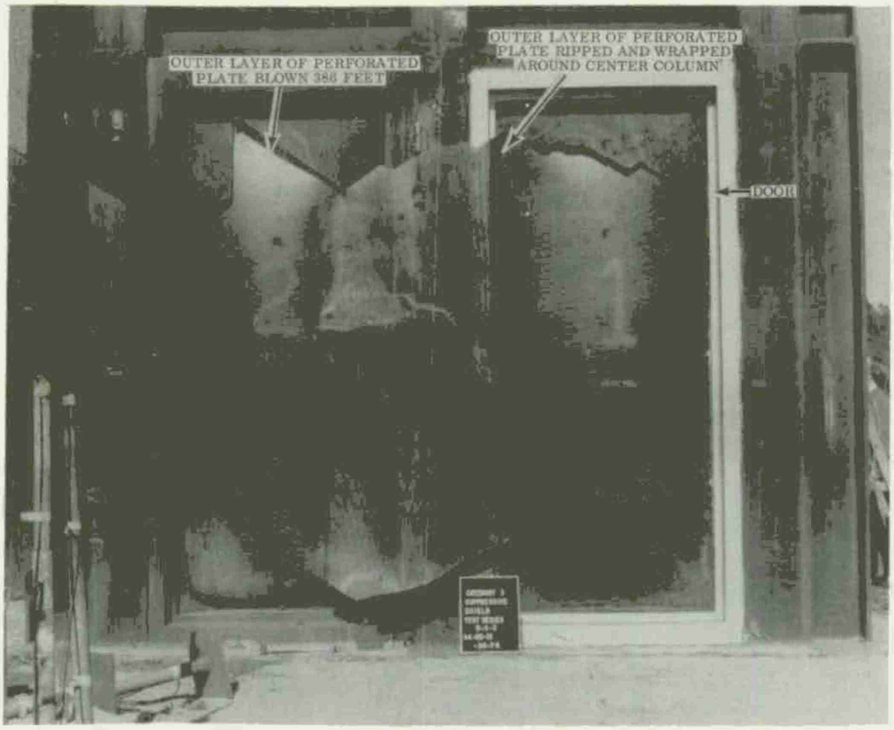



Figure 12. Category 3 S/S Damage From Test B3-2, Front Side

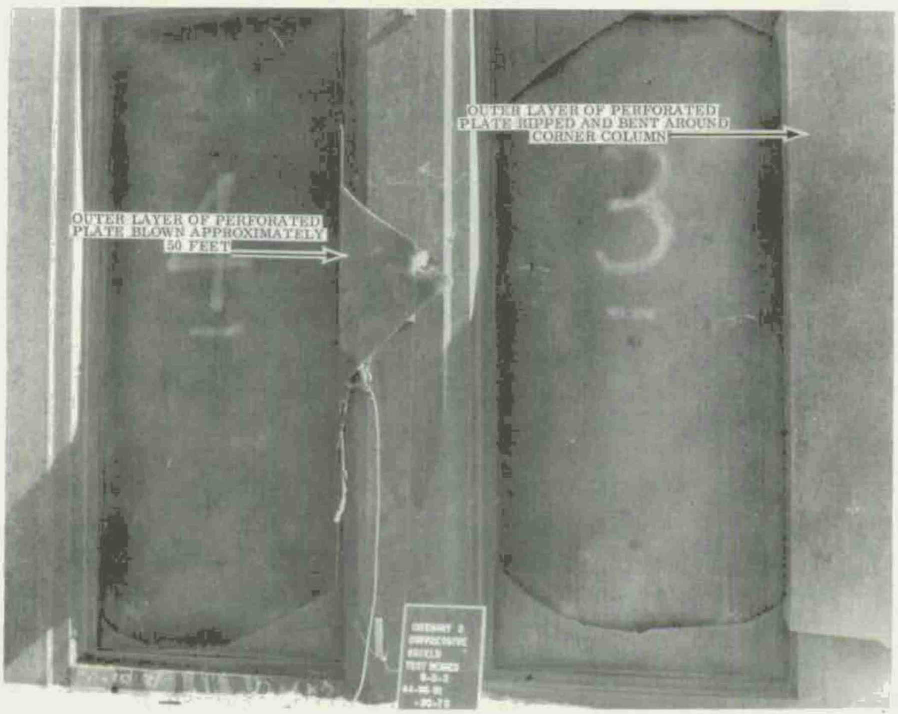



Figure 13. Category 3 S/S Damage From Test B3-2, Left Side

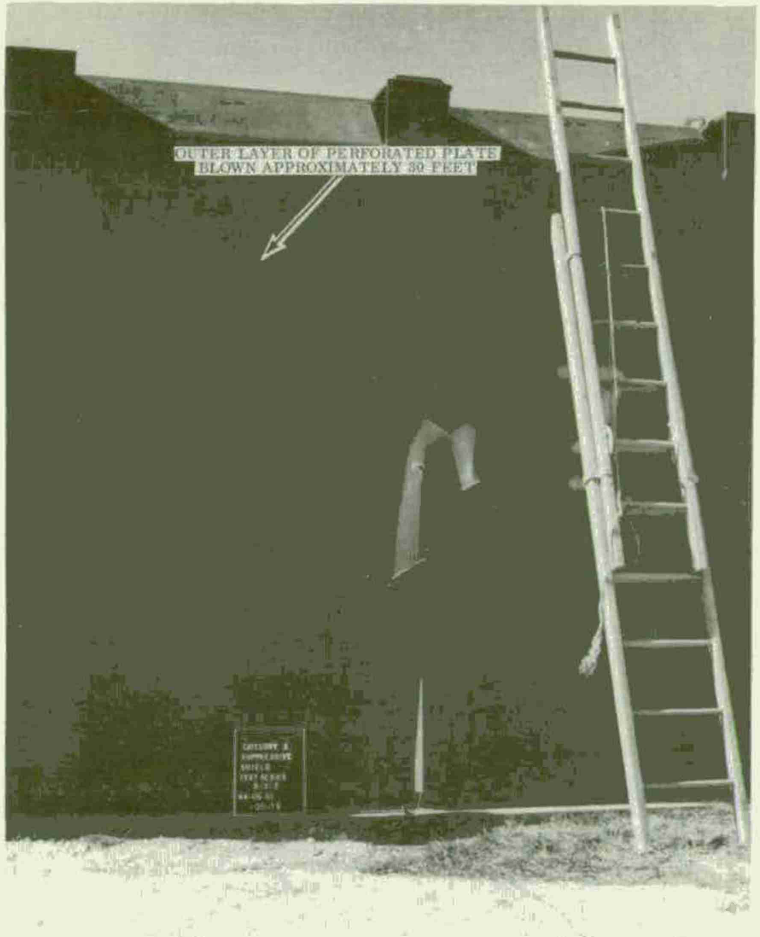



Figure 14. Category 3 S/S Damage From Test B3-2, Right Side

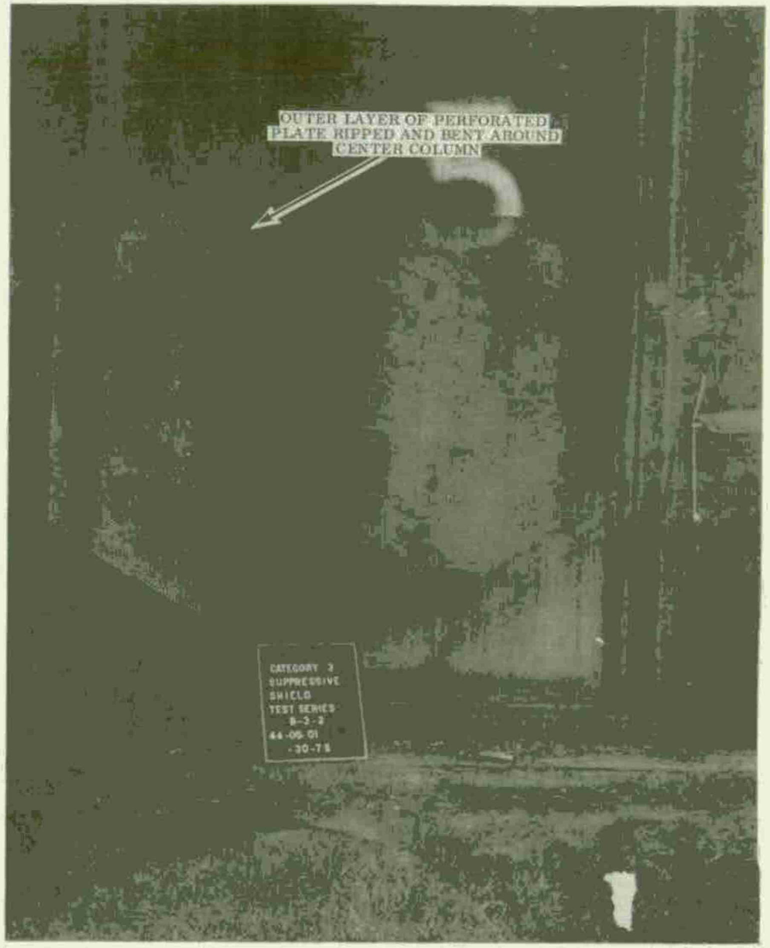



Figure 15. Category 3 S/S Damage From Test B3-2, Back Side


Figure 16. Category 3 S/S Damage From Test B3-2


Figure 17. Category 3 Test B3-1 Setup, Explosive Charge

The reasoning behind use of the new configurations were:

a. The venting of the inside or no. 1 layer was increased to reduce the loading on the angles and the panel frame where the failure occurred during test B3-1.

b. Sufficient additional angles were added to eliminate the "line of sight" problem.

c. The venting of the third and fourth perforated plates was reduced to further reduce the blast pressure.

d. The venting of the outer layer of perforated plates was increased from that of the two inner perforated plates to reduce loading of this plate and to prevent failure in tension as was experienced with one panel on test B3-1. The difference in blast pressure reduction using the two configurations was negligible.

e. Commercial availability of perforated plate within reasonable time frame of 90 days.

4.2.1 Side-On Blast Pressure Measurements. The side-on blast pressures measured with exterior ST-7H ballistic probes, exterior ST-2 ground mounts, and interior ST-7 ballistic probes are shown in tables 3, 4, and 5. The blast pressure reduction varied between 92 percent and 70 percent at distances from the exterior wall of 3 to 18 feet and the general trend is toward lower values at the larger distances. A plot of pressure reduction, % R, versus distance from charge, d, is shown in figure 18. To within a standard deviation of 5 percent, the curve is fit by the equation $\%R = 96 - 1.91\, d'$, where d' is the distance from the wall. The "characteristic" reduction extrapolated to the exterior wall surface is found to be 96 percent $\pm$ 4 percent. A plot of blast pressures as a function of distance from charge for exterior side-on measurements from all tests is shown in figure 19.

The close-in ground plane side-on blast pressure measurements showed consistently higher pressures than the ballistic probes at the same distance from the shield walls. Although little is known about the blast wave shape as it emerges from the ventilated panels, this higher pressure recorded at the ground plane was treated as though it was caused by the face-on component of the blast wave front dictated by the geometry of a test setup in free-field. Using correction factors from free-field tests given in US Army TM5-1300(9), these ground plane measurements then showed essentially the same pressures as recorded on the ballistic probes at the same distances from the shield wall. At greater distances from the shield where the vertical component of the blast wave front due to charge height is negligible, both transducer types yielded essentially the same pressure level.

4.2.2 Quasi-static Pressure. Test data indicates the maximum quasi-static pressure reached approximately 120-130 psi in the B3-X tests as recorded on the strain-gauge type pressure transducers. No attempt is made to present these pressures in tabular form since many variables are inherent in the tubing and orifices associated with the strain gauge pressure transducers. Figures 20 and 21 graphically illustrate the quasi-static pressures as recorded on magnetic tape and displayed on oscillograms from tests B2-X and B3-X respectively. The most consistent data was measured with the transducer attached to the 43-inch-long 1/4-inch-diameter stainless steel coiled tube.

Table 3. Category 3 S/S Test B1-1 Side-on Blast Pressure Measurements

| Test No. Charge Weight (lbs.) | Type of Transducer Mounting | Distance From Charge (Ft.) | Z $(Ft. W^{-1/3})$ | Pressure Side-on (psi) (Soroka) | Pressure Side-on (psi) (Test) | Pressure Reduction (%) | Arrival Time (ms) |
|---|---|---|---|---|---|---|---|
| B1-1/5.0 | Ballistic | 5.2 | 3.07 | 107.5 | 120. | N/A | .80 |
| B1-1/5.0 | Ballistic | 5.2 | 3.07 | 107.5 | xx | N/A | .85 |
| B1-1/5.0 | Ballistic | 8.5 | 4.97 | 34.2 | 3.7 | 89 | 2.7 |
| B1-1/5.0 | Ballistic | 9.0 | 5.26 | 29.9 | 2.7 | 91 | 3.4 |
| B1-1/5.0 | Ground | 10.0 | 5.85 | 23.3 | 1.8* | 92 | 6.7 |
| B1-1/5.0 | Ballistic | 11.5 | 6.72 | 17.1 | 2.4 | 86 | 5.8 |
| B1-1/5.0 | Ballistic | 12.0 | 7.02 | 15.5 | 1.9 | 88 | 5.8 |
| B1-1/5.0 | Ground | 13.0 | 7.60 | 13.1 | 1.4* | 89 | 9.2 |
| B1-1/5.0 | Ballistic | 14.5 | 8.48 | 10.4 | 1.4 | 87 | 8.4 |
| B1-1/5.0 | Ballistic | 15.0 | 8.77 | 9.7 | 1.1 | 89 | 8.6 |

* Pressure corrected for face-on component per TM5-1300.

Table 4. Category 3 S/S Tests B2-1 and B2-2 Side-on Blast Pressure Measurements

| Test No. Charge Weight (lbs.) | Type of Transducer Mounting | Distance From Charge (Ft.) | Z $(Ft. W^{-1/3})$ | Pressure Side-on (psi) (Soroka) | Pressure Side-on (psi) (Test) | Pressure Reduction (%) | Arrival Time (ms) |
|---|---|---|---|---|---|---|---|
| B2-1/11.8 | Ballistic | 5.2 | 2.31 | 202.5 | 210 | N/A | 0.72 |
| B2-1/11.8 | Ballistic | 5.2 | 2.31 | 202.5 | 175 | N/A | xx |
| B2-2/11.6 | Ballistic | 9.7 | 4.28 | 48.8 | 8.6 | 82 | 3.83 |
| B2-2/11.6 | Ground | 9.9 | 4.39 | 46.0 | 7.7 | 83 | 3.47 |
| B2-1/11.8 | Ballistic | 11.5 | 5.05 | 32.9 | 3.8 | 88 | 5.50 |
| B2-1/11.8 | Ballistic | 12.0 | 5.27 | 29.8 | 2.5 | 92 | 5.70 |
| B2-2/11.6 | Ballistic | 12.3 | 5.43 | 27.8 | 4.8 | 80 | 5.79 |
| B2-2/11.6 | Ground | 12.9 | 5.71 | 24.7 | 5.5 | 78 | 5.63 |
| B2-1/11.8 | Ground | 13.0 | 5.71 | 24.7 | 2.1 | 91 | 8.70 |
| B2-2/11.6 | Ballistic | 15.1 | 6.68 | 17.3 | 3.0 | 83 | 6.93 |
| B2-1/11.8 | Ground | 16.0 | 7.03 | 15.5 | 2.3 | 85 | 10.9 |
| B2-1/11.8 | Ballistic | 17.5 | 7.69 | 12.7 | 3.7 | 71 | 10.3 |
| B2-1/11.8 | Ballistic | 18.0 | 7.91 | 12.0 | 2.3 | 81 | 10.8 |
| B2-2/11.6 | Ballistic | 18.1 | 8.01 | 11.7 | 3.2 | 73 | 10.6 |
| B2-2/11.6 | Ground | 19.1 | 8.43 | 10.5 | 2.8 | 74 | 10.8 |
| B2-2/11.6 | Ballistic | 21.1 | 9.34 | 8.6 | 3.1 | 64 | 13.0 |
| B2-1/11.8 | Ballistic | 23.5 | 10.33 | 7.1 | 3.2 | 55 | 15.2 |
| B2-1/11.8 | Ballistic | 24.0 | 10.55 | 6.8 | 1.8 | 74 | 16.2 |
| B2-2/11.6 | Ballistic | 24.2 | 10.70 | 6.6 | 2.9 | 56 | 15.5 |
| B2-2/11.6 | Ground | 25.4 | 11.21 | 6.1 | 2.3 | 62 | 15.6 |
| B2-2/11.6 | Ballistic | 27.3 | 12.05 | 5.4 | 2.4 | 56 | 17.8 |
| B2-2/11.6 | Ballistic | 30.2 | 13.34 | 4.5 | 2.2 | 53 | 20.15 |
| B2-2/11.6 | Ground | 31.2 | 13.76 | 4.3 | 2.0 | 54 | 20.66 |
| B2-2/11.6 | Ballistic | 33.2 | 14.68 | 3.9 | 2.3 | 46 | 22.65 |
| B2-2/11.6 | Ballistic | 36.2 | 15.01 | 3.4 | 1.9 | 45 | 24.94 |
| B2-2/11.6 | Ground | 37.3 | 16.46 | 3.2 | 1.4 | 55 | 25.69 |

Table 5. Category 3 Suppressive Shield Tests B3-1 and B3-2 Side-on Blast Pressure Measurements

| Test No. Charge Weight (lbs) | Type of Transducer Mounting | Distance From Charge (Ft.) | Z $(Ft. W^{-1/3})$ | Pressure Side-on (psi) (Soroka) | Pressure Side-on (psi) (Test) | Pressure Reduction (%) | Arrival Time (ms) |
|---|---|---|---|---|---|---|---|
| B3-1/57.2 | Ballistic | 5.2 | 1.36 | 556 | 590 | N/A | 0.12 |
| B3-1/57.2 | Ballistic | 5.2 | 1.36 | 556 | 570 | N/A | 0.12 |
| B3-2/59.9 | Ballistic | 9.9 | 2.52 | 168 | 25.0 | 85 | 2.60 |
| B3-2/59.9 | Ground | 10.3 | 2.63 | 151.9 | 35.3 | 77 | 2.06 |
| B3-2/59.9 | Ballistic | 12.4 | 3.17 | 99.2 | 15.3 | 84 | 4.27 |
| B3-2/59.9 | Ground | 12.9 | 3.30 | 90.8 | 14.4 | 84 | xx |
| B3-2/59.9 | Ballistic | 15.1 | 3.87 | 62.2 | 18.7 | 70 | 6.23 |
| B3-1/57.2 | Ground | 16.0 | 4.15 | 52.6 | 4.9 | 91 | 8.40 |
| B3-2/59.9 | Ballistic | 17.7 | 4.52 | 42.8 | 10.8 | 75 | 8.10 |
| B3-1/57.2 | Ballistic | 18.0 | 4.67 | 39.7 | 12.0 | 70 | 8.30 |
| B3-2/59.9 | Ground | 18.5 | 4.73 | 38.5 | 21.5 | 44 | 7.84 |
| B3-1/57.2 | Ballistic | 19.0 | 4.93 | 34.9 | xx | xx | xx |
| B3-2/59.9 | Ballistic | 20.8 | 5.33 | 29.0 | 11.8 | 59 | 10.27 |
| B3-2/59.9 | Ballistic | 23.8 | 6.08 | 21.4 | 10.1 | 53 | 11.25 |
| B3-2/59.9 | Ground | 24.3 | 6.21 | 20.4 | 8.1 | 60 | 12.03 |
| B3-2/59.9 | Ballistic | 26.7 | 6.83 | 16.5 | 9.1 | 45 | 14.35 |
| B3-2/59.9 | Ballistic | 29.7 | 7.59 | 13.1 | 10.5 | 20 | 16.49 |
| B3-2/59.9 | Ground | 30.2 | 7.72 | 12.6 | 9.7 | 23 | 16.40 |
| B3-2/59.9 | Ballistic | 32.7 | 8.34 | 10.8 | 6.0 | 44 | 18.81 |
| B3-2/59.9 | Ballistic | 35.7 | 9.12 | 9.0 | 4.4 | 51 | 21.21 |
| B3-2/59.9 | Ground | 36.1 | 9.23 | 8.8 | 5.5 | 38 | 21.04 |

The ST-2 and PCB transducers gave questionable quasi-static pressure data due to the accelerometer affect of the piezoelectric crystal sensing elements. For tests B1-1, B2-1 and B3-1 these transducers were mounted in the center of the panels which tend to amplify the problem due to panel movement. For tests B2-2 and B3-2 these transducers were mounted in the frame members but still suffered from "ringing" although shock mounted with o-rings.

4.2.3 Face on Blast and Reflected Pressures. Reflected pressure measurements data are given in table 6. Data from test B1 showed expected results. Tests B2-1 and B2-2 both indicated the initial peak blast pressure on the ceiling was twice that calculated. It was decided the stainless steel hopper, open at the top with a funnel-shaped bottom, caused a focusing of reflected blast pressure upward toward the roof. The standoff distance of the charge from the bottom of the hopper was less than 1/2 the diameter of the charge (Reference figures 1, 2, and 3).

Test B3-1 showed the peak reflected pressure to be highest (5400 psi) at the wall adjacent to the wall where the two panels were ejected. Reflected pressure at the floor-to-wall interesection opposite the latter wall indicated the lowest pressure (2000 psi). The wide variation in reflected pressure recorded in test B3-1 may have been due to the 4 gms of PETN used as a booster for the 57.2-pound charge which may have prevented symmetrical detonation of the charge.

Table 6. Category 3 Suppressive Shield Explosive Containment Tests B1-1, B2-1, 2 and B3-1,2 Reflected Blast Overpressures

| Distance From Charge (Ft.) | Charge Weight (lbs) | Z (Ft.W$^{-1/3}$) | Calculated Reflected Pressure (psi) | Actual Reflected Pressure (psi) | Arrival Time (ms) |
|---|---|---|---|---|---|
| Wall | | | | | |
| 5.16 | 5.0 | 3.02 | 570 | 610* | 0.82 |
| 48" - Height | 5.0 | 3.02 | 570 | 630 | 0.83 |
| | 11.6 | 2.28 | 1265 | 1680 | 0.70 |
| | 11.8 | 2.27 | 1280 | 800 | 0.93 |
| | 11.8 | 2.27 | 1280 | 1200 | 0.73 |
| | 57.2 | 1.34 | 4150 | 5400* | 0.43 |
| | 57.2 | 1.34 | 4150 | 4200* | 0.42 |
| | 59.9 | 1.32 | 4300 | 5700* | 0.40 |
| Ceiling | | | | | |
| 5.60 | 5.0 | 3.27 | 450 | 640* | 0.88 |
| | 11.6 | 2.47 | 1010 | 2100 | 0.56 |
| | 11.8 | 2.46 | 1025 | 1975 | 0.51 |
| | 57.2 | 1.45 | 3625 | 3675* | 0.52 |
| Floor | | | | | |
| 7.51 | 5.0 | 4.39 | 180 | 180* | 1.76 |
| 6" - Height | 11.8 | 3.30 | 435 | 510 | 1.08 |
| | 57.2 | 1.95 | 1875 | 1880 | 0.85 |
| Corners | | | | | |
| 7.5 | 11.8 | 3.31 | 435 | 336 | 1.34 |
| 48" - Height | 11.8 | 3.31 | 435 | 346 | 1.10 |
| | 59.9 | 1.92 | 1940 | 3050** | 0.74 |
| | 59.9 | 1.92 | 1940 | 3327** | 0.71 |

* Average of measured values calculated from measured arrival times when within experimental accuracy.

** Maximum recorded at 4th peak.

For the tests B2-2 and B3-2, the corners were instrumented in order to find the impulse that was affecting the panels due to the cubical configuration of the shield. Figure 22 shows the pressure-time history of two adjacent corners and the wall between. Calculated impulse for the corners was 19.7 psi-sec and 12.9 psi-sec compared with 12.8 psi-sec for the wall nearest the charge, even though the initial peak pressure at the wall was approximately twice the initial peak pressure in the corners.

4.3 Fragmentation Test Results. In addition to providing blast pressure and structural response data, test series B2 was designed to measure the capability of the shield to retain fragments that can be expected from the candidate operation. The fragment threat of the candidate operation is typified by recovery of fragments shown in figures 23 and 24. The worst case fragments were those originating from the 16-gauge stainless steel hopper rather than the cast-iron bracket as had been anticipated in the initial design. Both tests

B2-1 and B2-2 inflicted similar damage to the shield and yielded the same general type and size of fragments. Fragment damage to the shield walls is shown in figures 25 through 28. The wall panels suffered severe fragment damage to the inside layer of perforated plates and the concrete floor. No damage occurred to the ceiling panels. One fragment (approximately 1-1/2" x 3/8" x 16 gauge) from test B2-1 penetrated the shield and escaped. The penetration, however, was in an area of "poor fit" or gap between the panels and the main frame, which afforded only a 3/8-inch single steel thickness rather than the 3/4-inch spaced armor design requirement. This gap was eliminated when the new panels were installed for test B2-2 and no fragments escaped the shield. During test B2-1, one fragment penetrated the flange of a wall column 1.1 inches thick but was retained by the shield. In test B2-2 fragment penetrations in the frame member and panel frame angles greater than .85 inches were observed, but all fragments were retained inside the shield.

## 5.0 CONCLUSIONS

The candidate Category 3 suppressive shield did not withstand the proof pressure test. The test program demonstrated the following:

1. The main structural frame is capable of withstanding blast and quasi-static pressure loading caused by 130 percent overcharge (59.9 lb.) of design explosive weight (46 lb.).

2. The panel configuration (i.e., 1-layer 10 ga. perforated plate, 1-layer 2-1/2" x 2-1/2" x 3/16" fragmentation layer followed by three additional layers of 1 ga. perforated plate) is capable of stopping the fragments that can be expected from the candidate operation although the fragment threat is considerably greater than had been previously estimated. The spaced armor effect appears to offer a reduction of metal thickness required.

3. The panel configuration is capable of reducing blast pressures on the order of 80-90 percent at distances close to the shield wall, as required in the design guidelines.

4. Additional research is required in the area of panel design and attachment of the venting members to structural frames. The addition of small frame members (e.g., 3-inch I-beams) across the panel openings on the outside of the shield would probably have prevented the outer layer of perforated steel plates from becoming secondary fragments and would have enabled the shield to be qualified and safety approved for its intended application.

5. Immediate attention should be focused upon the substitution of materials in machine/processing equipment of all AAP's with regard to the secondary fragments produced by accidental explosions.

Due to the symmetrically concentric dimensions of the test setup (reference figures 1 and 3), similar fragments could be expected in all directions (360°) from the horizontal to vertical plane of revolution (with the possible exception of the area affected by the hopper/bracket interface at about 55°). The fragment causing the 1.1-inch penetration was propelled from the hopper approximately 90° counterclockwise from the area of the bracket as shown in figure 1. It can be concluded from the results of both tests B2-1 and B2-2 that the "spaced armor" effect of the suppressive shield panels with total steel thickness of approximately

0.78 inches was more effective in stopping high energy fragments than the solid 1.1-inch thick steel plate where a penetration was observed. Similar phenomena was experienced during tests associated with the 81 mm suppressive shield. In propagation test of 81-mm HE rounds, a camera bunker (1-inch-thick mild steel) was penetrated by an 81-mm fragment. Subsequent testing of the 81-mm suppressive shield with up to six 81-mm HE rounds, showed that no fragment penetrated the full panel thickness (13/16-inch) during any of the tests. Additional investigation into the effectiveness of suppressive shield spaced armor in stopping HE fragments is suggested.

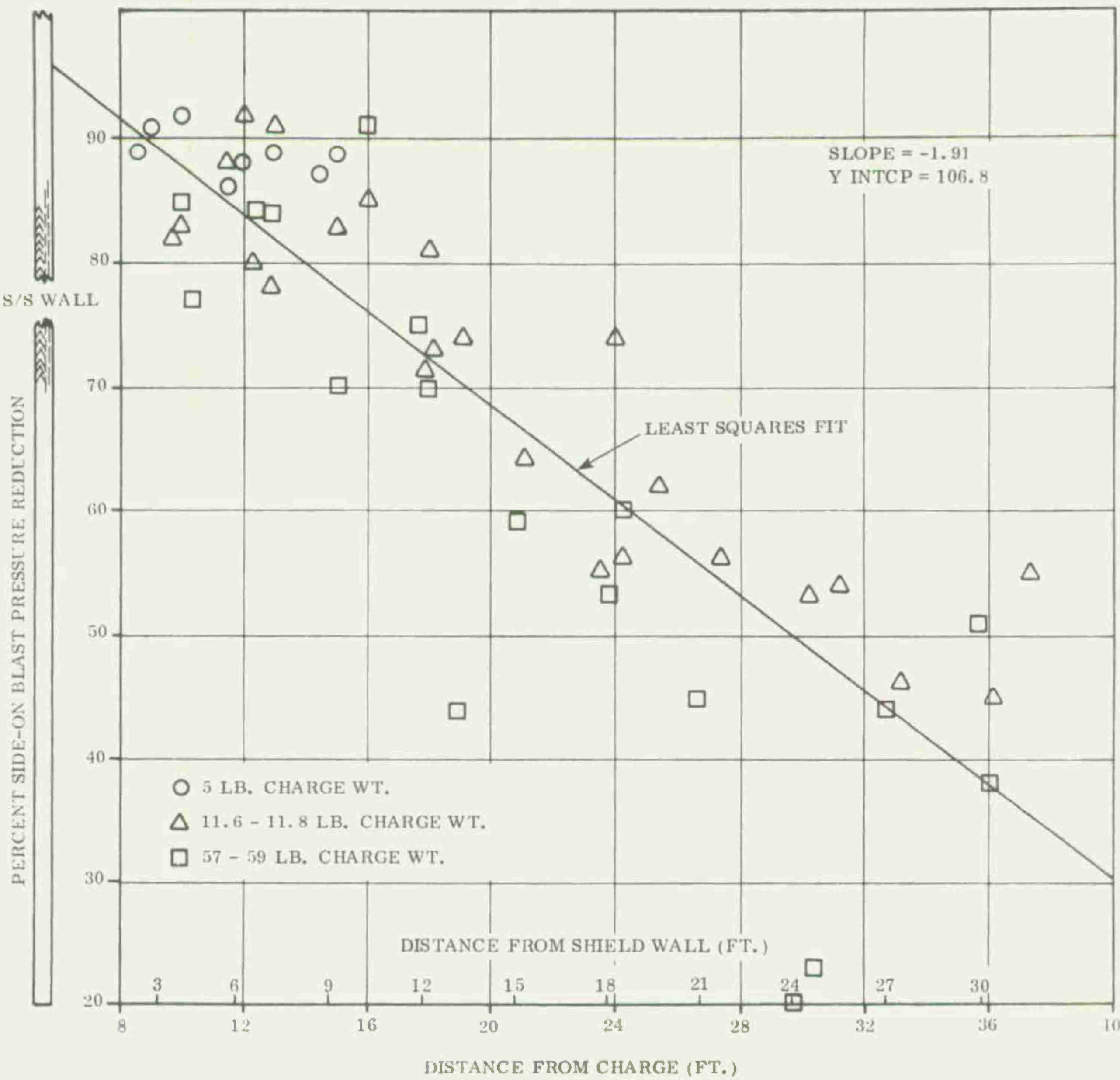



Figure 18. Category 3 Suppressive Shield Percent Reduction of Side-on Blast Pressure Versus Distance from Change (Ft.) Tests B1-1, B2-1, 2, B3-1,2.

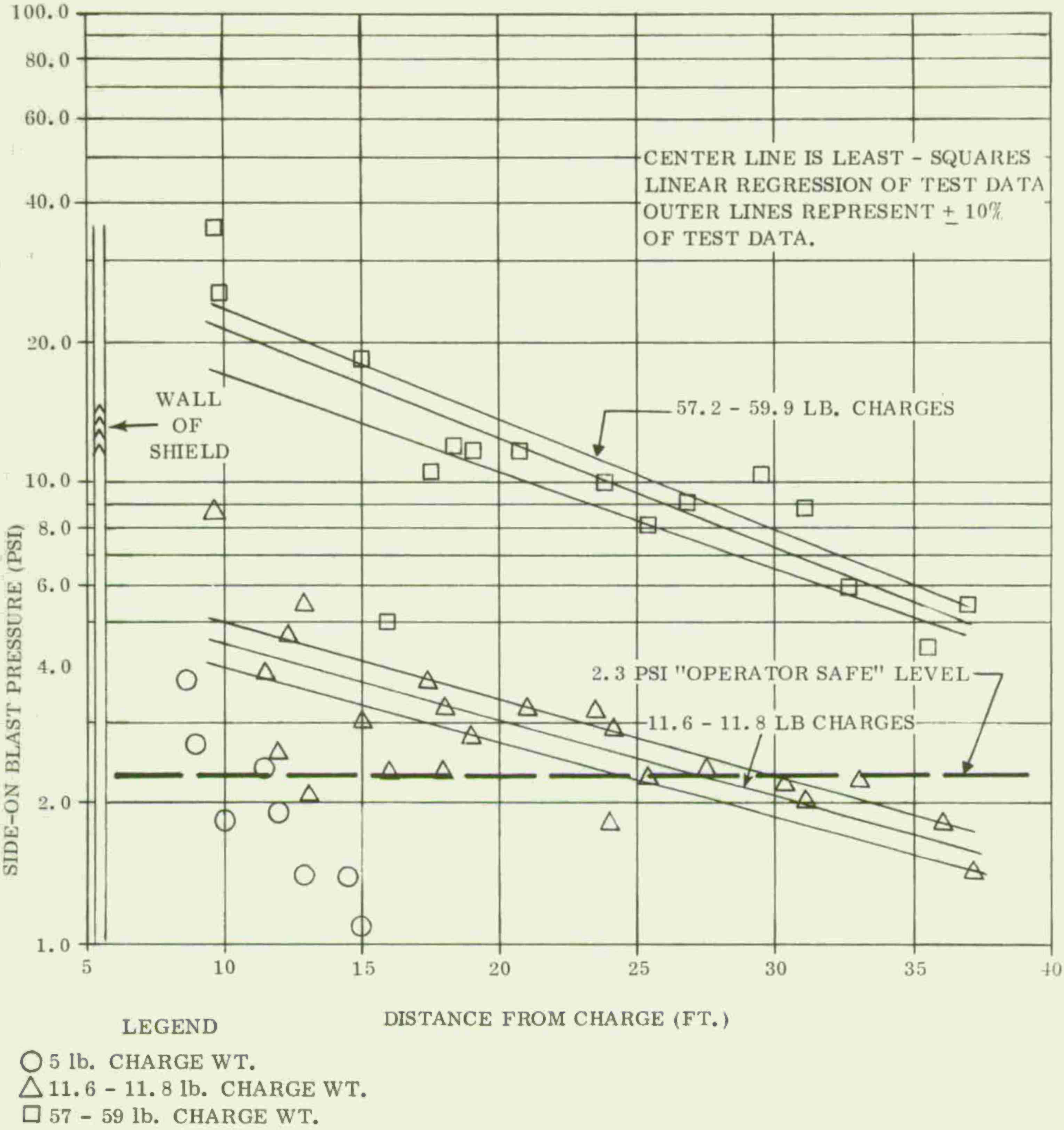



Figure 19. Category 3 Suppressive Shield External Side-On Blast Pressure (PSI) Versus Distance from Charge (Ft.)

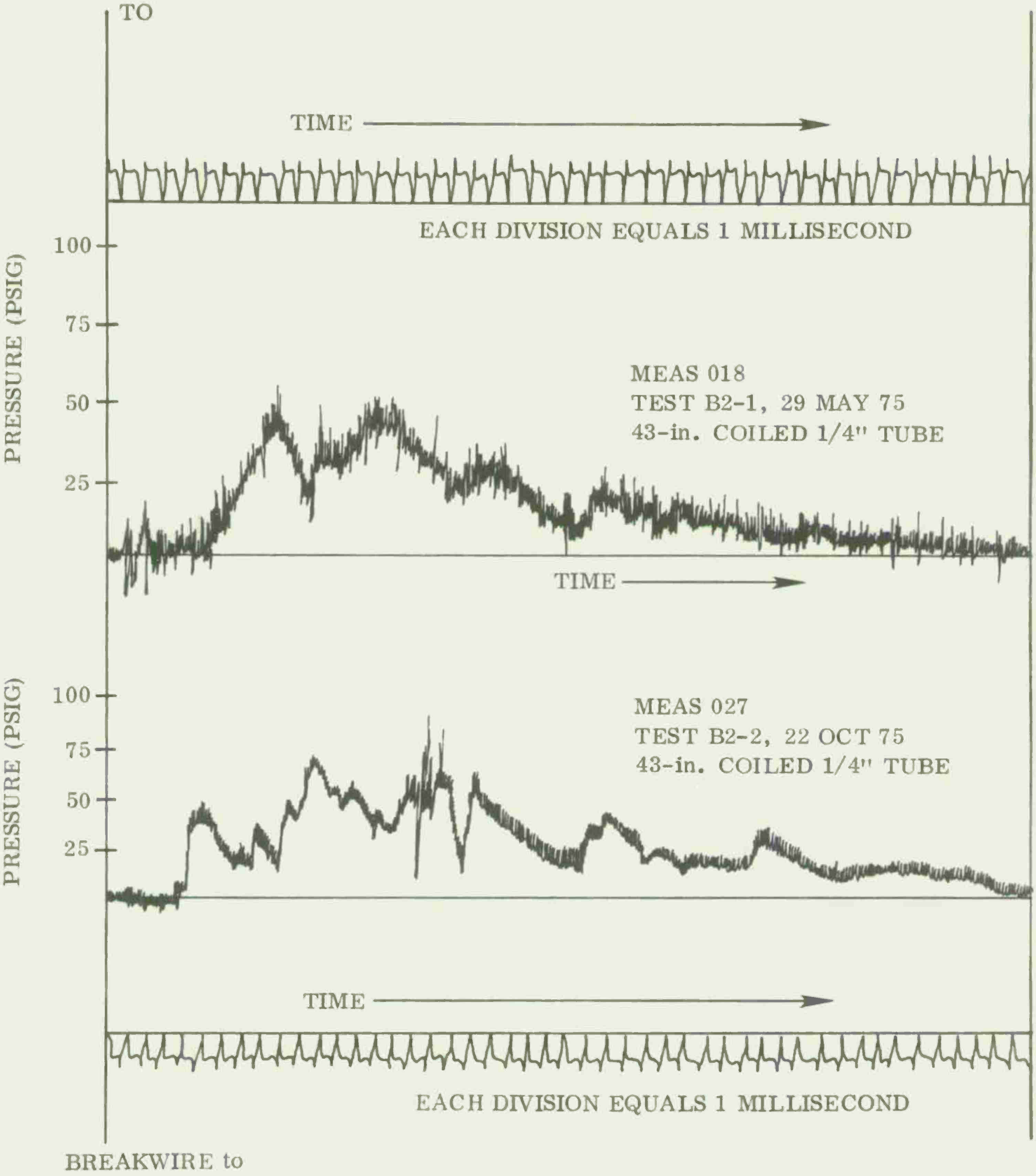



Figure 20. Category 3 Test Series B2, Fragmentation Tests, Quasi-Static Pressure versus Time (Psig versus MS)

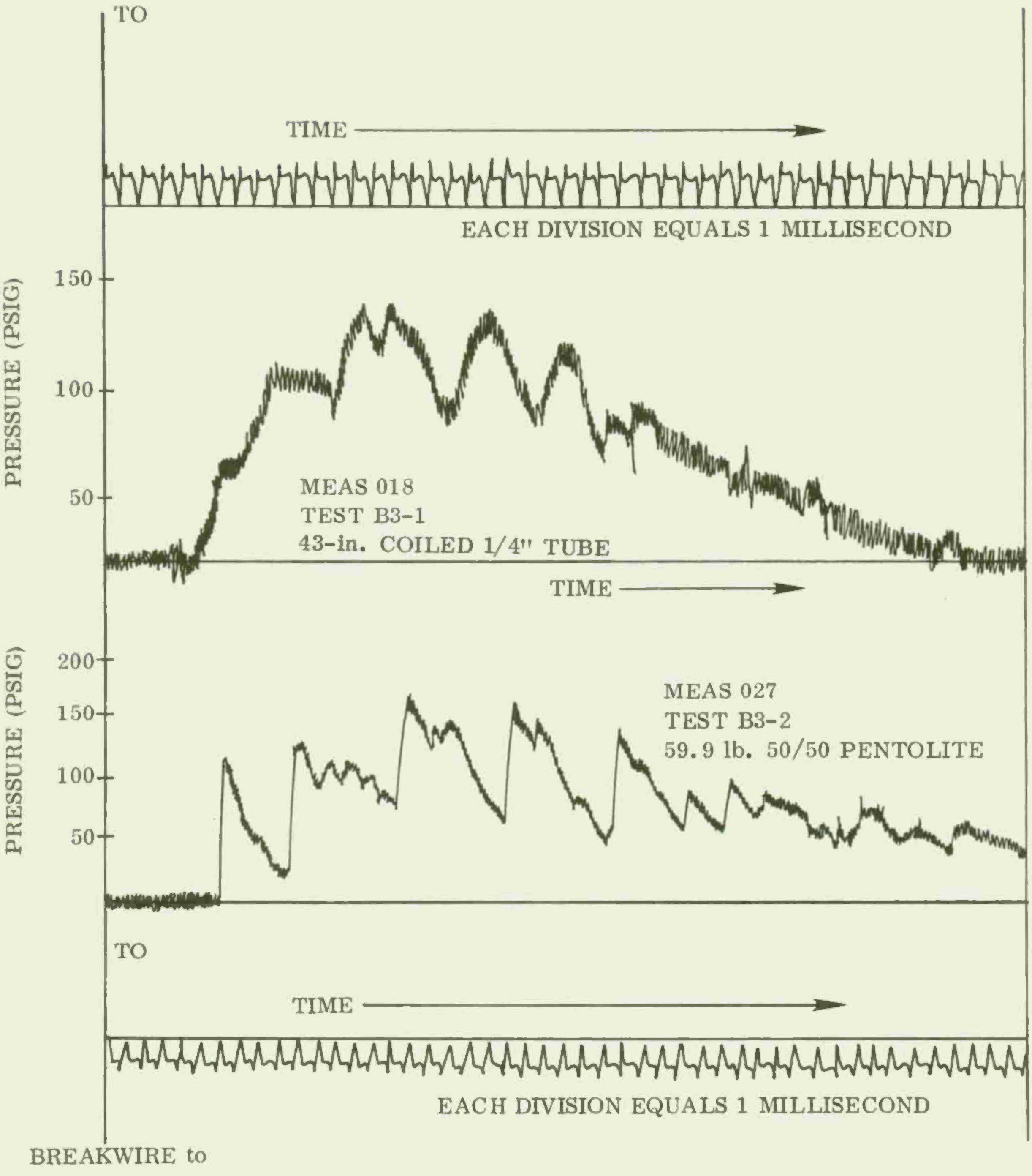



Figure 21. Category 3 Test Series B3 Quasi-Static Pressure versus Time (Psig versus MS)

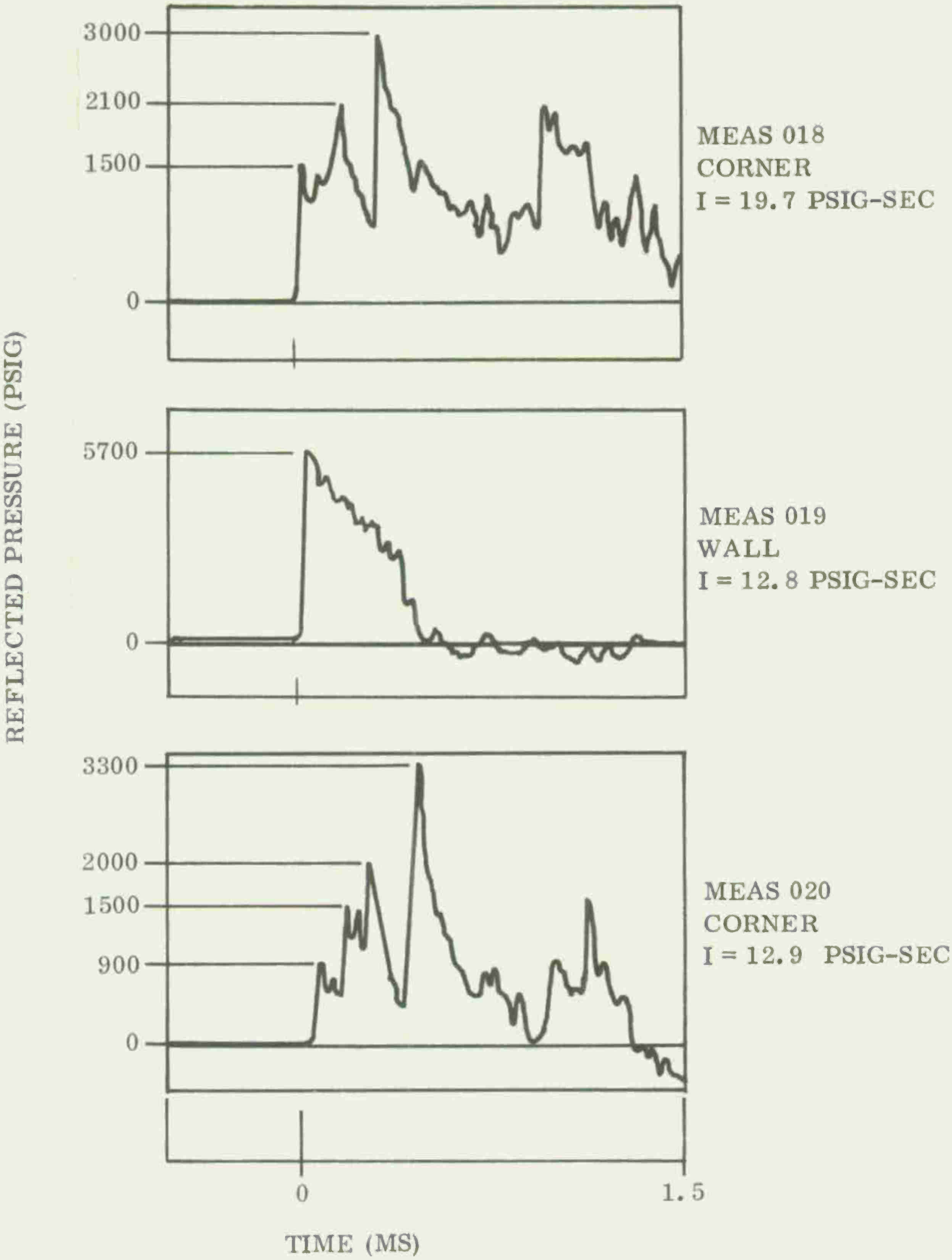



Figure 22. Category 3 Suppressive Shield Pressure (PSIG) versus Time (MS) Test B3-2 Reflected Pressures

Figure 23. Category 3 16-Gauge Stainless Steel Hopper Fragmentation Threat

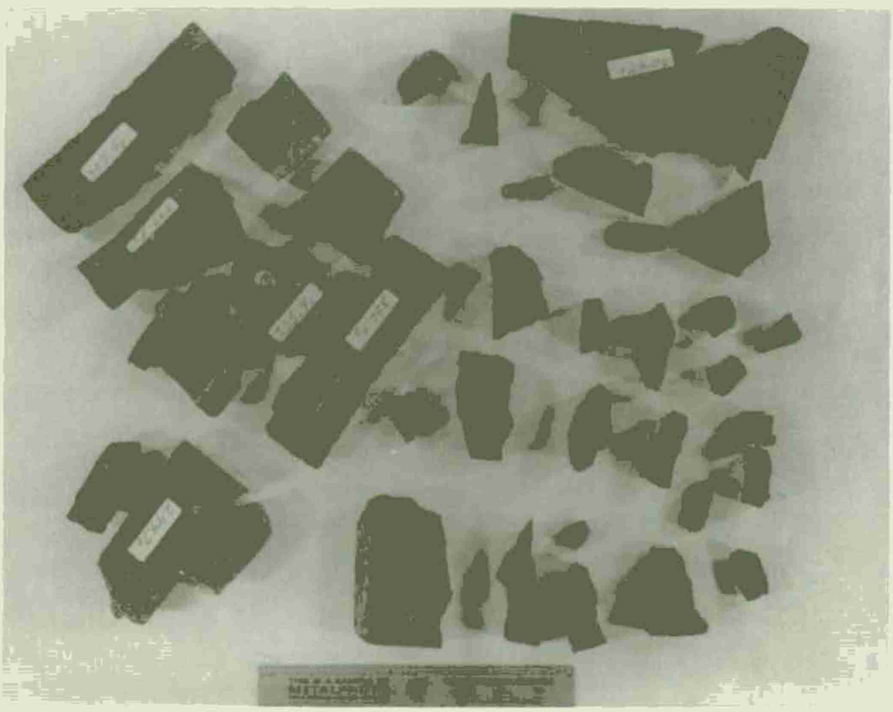


Figure 24. Category 3 Cast Iron Bracket Fragmentation Threat

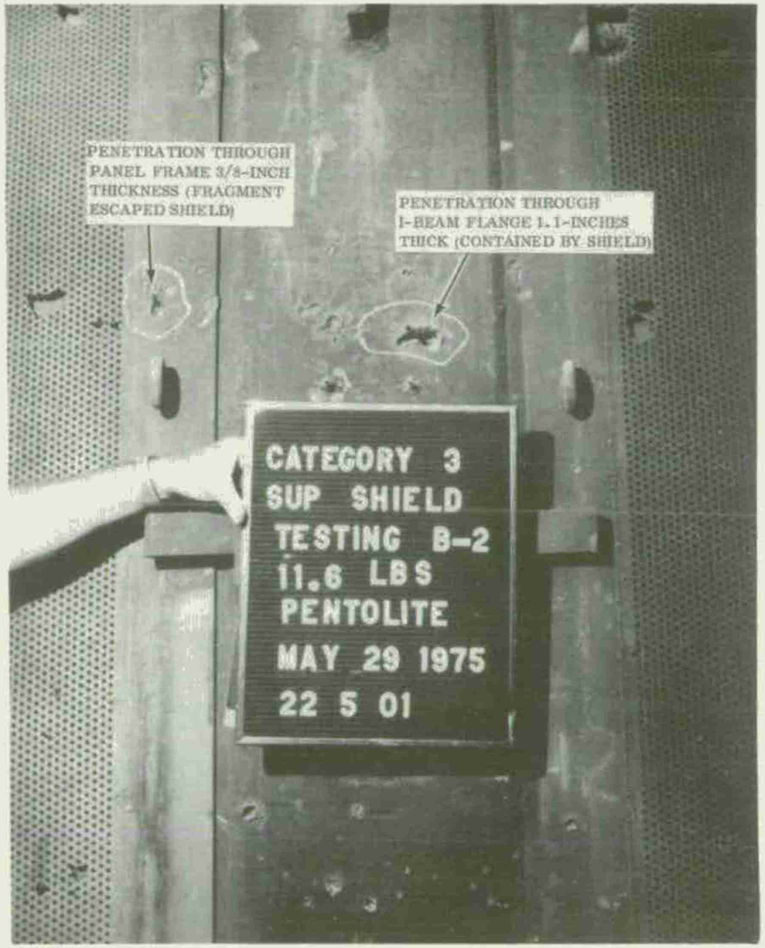



Figure 25. Category 3 Test B2-1 Fragmentation Test Results

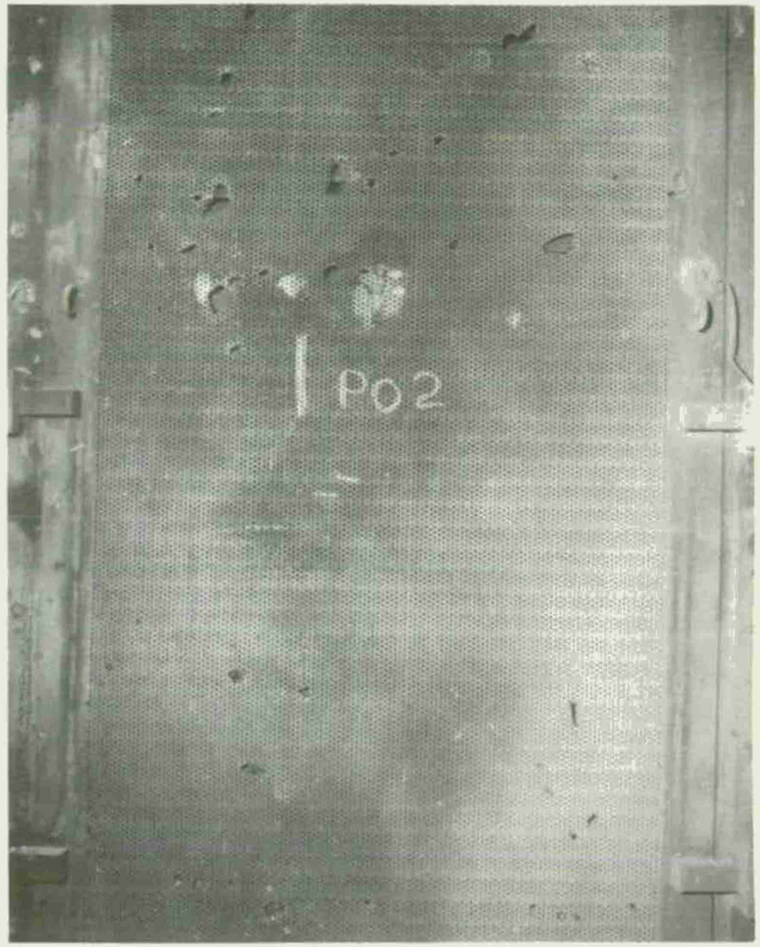



Figure 26. Category 3 Test B2-1, Typical Fragment Damage

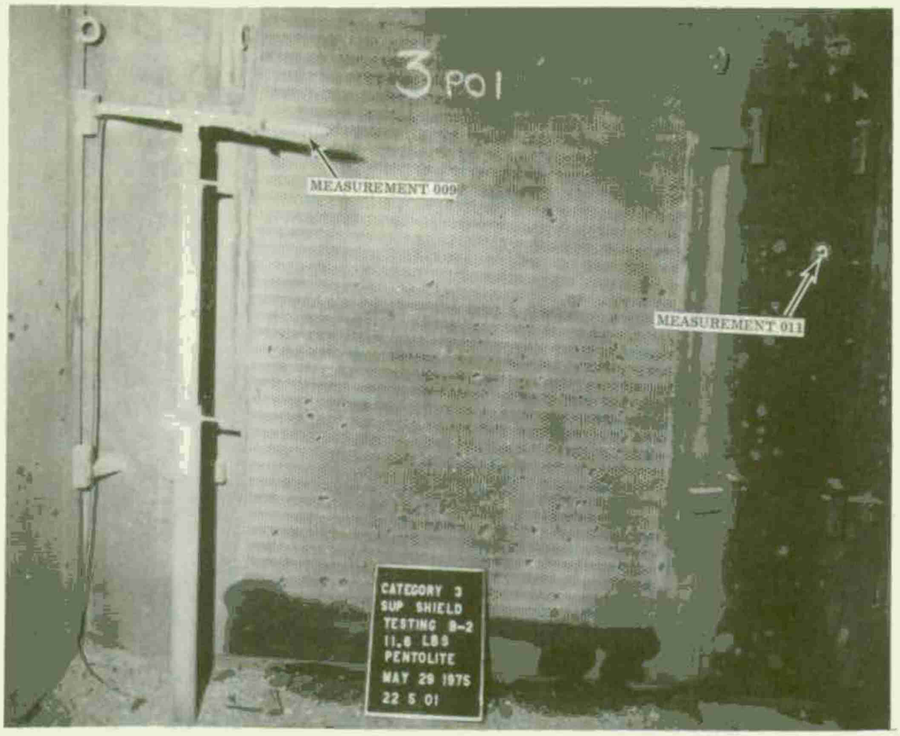



Figure 27. Category 3 Test B2-1, Typical Fragment Damage

Figure 28. Category 3, Test B2-1, Typical Fragment Damage to Concrete Floor

## REFERENCES CITED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3. General Electric Contractor Report No. EA-FR-2A07, Final Report on Design, Fabrication and Test of Prototype Transportable Suppressive Structure, December 1973.

4. Edgewood Arsenal Contractor Report No. EM-CR-74050, EA-4E35F, 81MM Suppressive Shield, March 1975.

5. Test Specifications for Category 3 Suppressive Shield Revision A, April 1975 and Revision E, EARL-EA-4133, September 1975.

6. BRL Report No. 1092, "Compiled Free-Air Blast Data on Bare Spherical Pentolite" February, 1960. (In conjunction with Soroka's Air Blast Tables.)

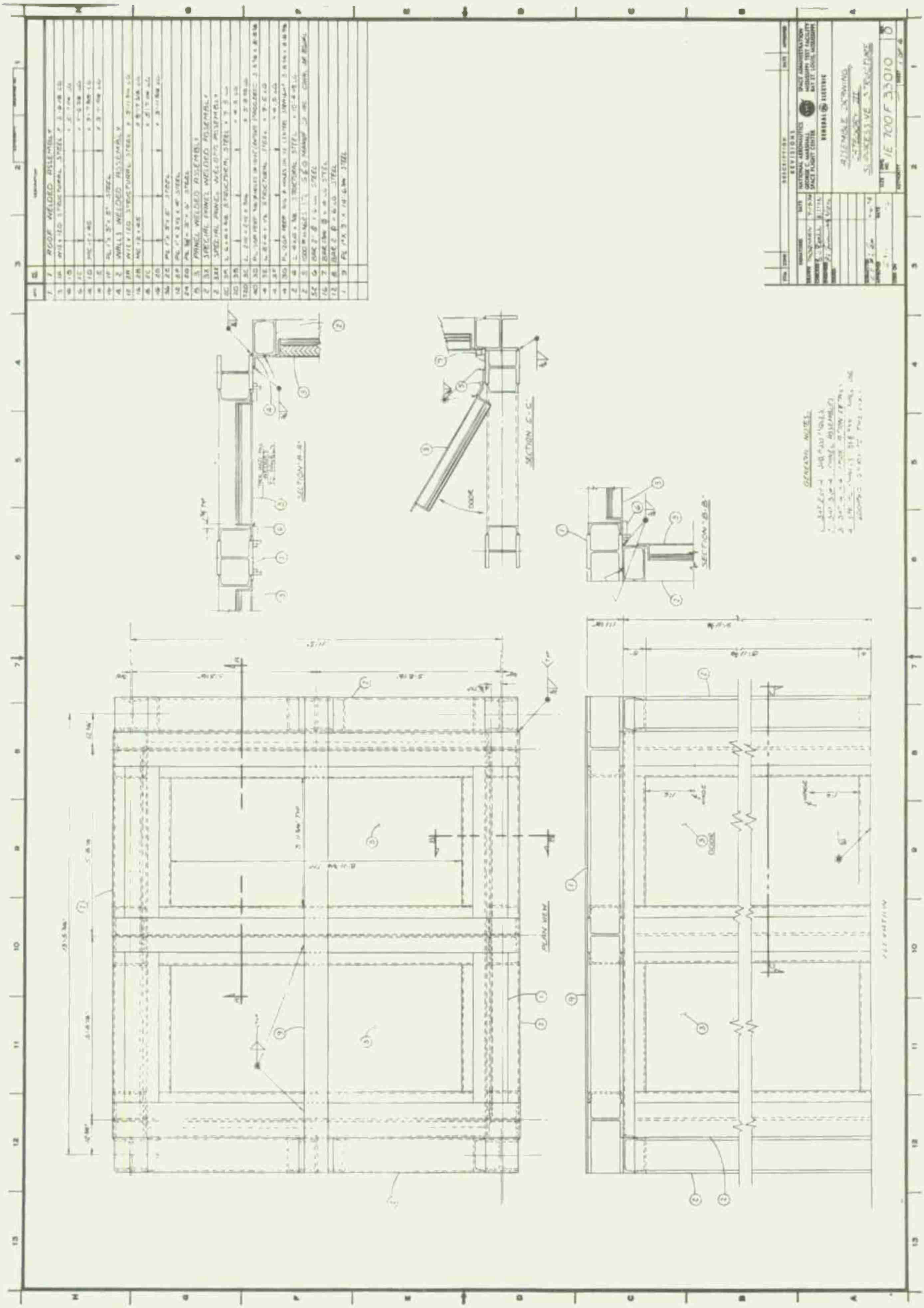
7. BRL Interim Memorandum Report No. 376, Blast Attenuation Outside Cubical Enclosure Made Up of Selected Suppressive Structure Panel Configurations, April 1975.

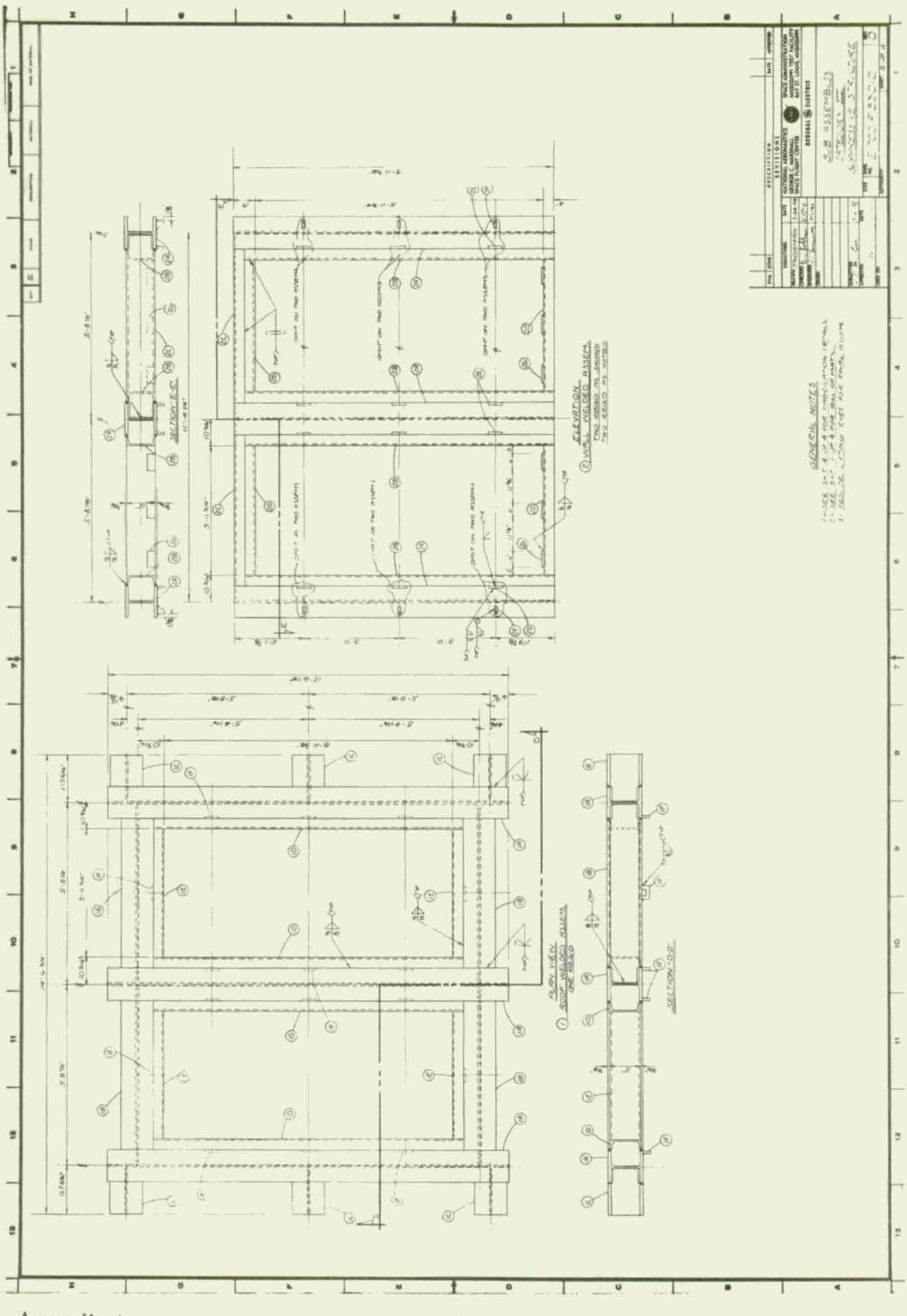
8. SwRI Report "Category V and III Suppressive Shields Strain Data", December 1975.

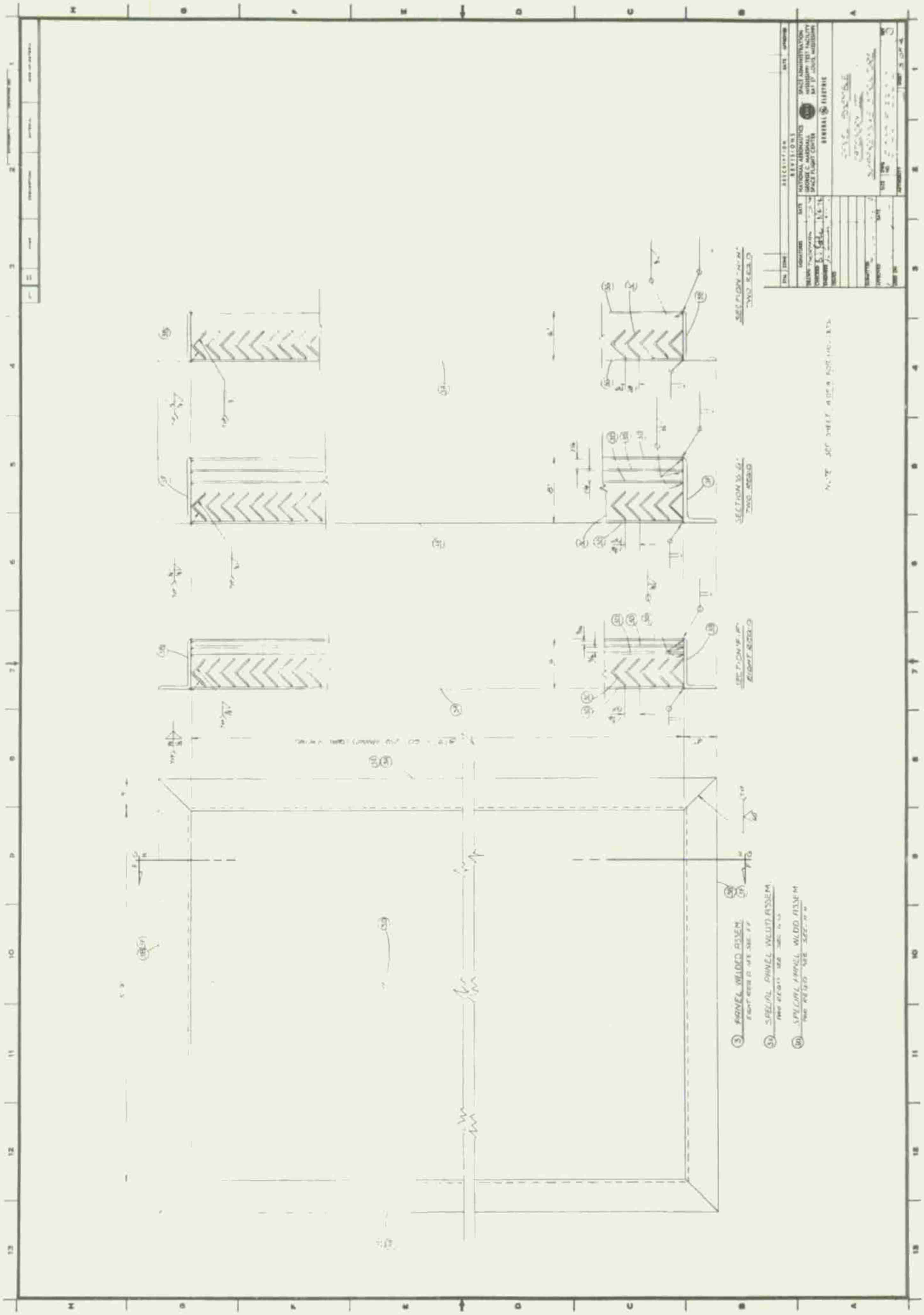
9. Department of the Army Technical Memorandum TM5-1300, Structure to Resist the Effects of Accidental Explosions, June 1969.

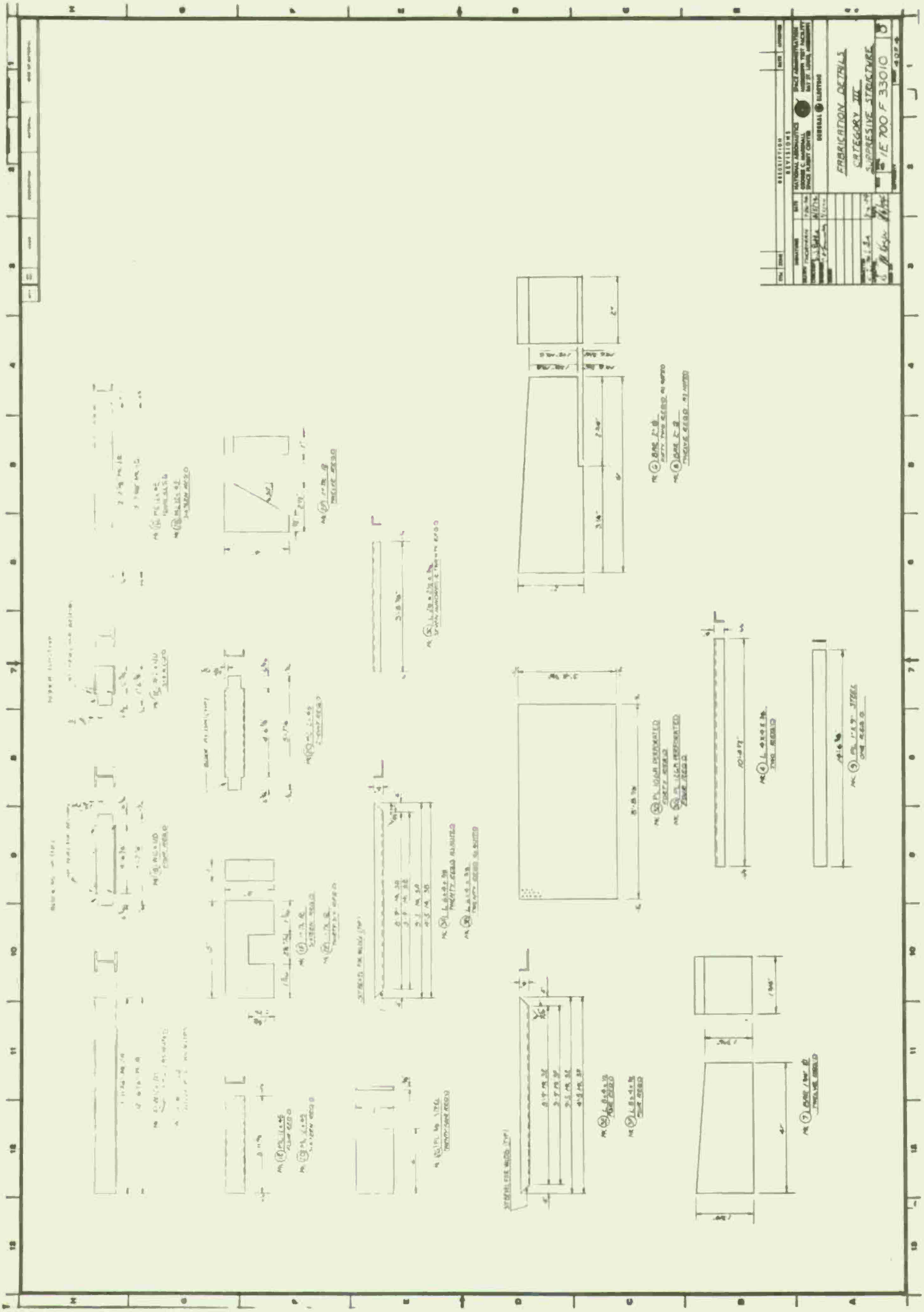
## APPENDIX A

### CATEGORY 3 SUPPRESSIVE STRUCTURE DESIGN DRAWINGS AND PHOTOGRAPH AS ORIGINALLY FABRICATED







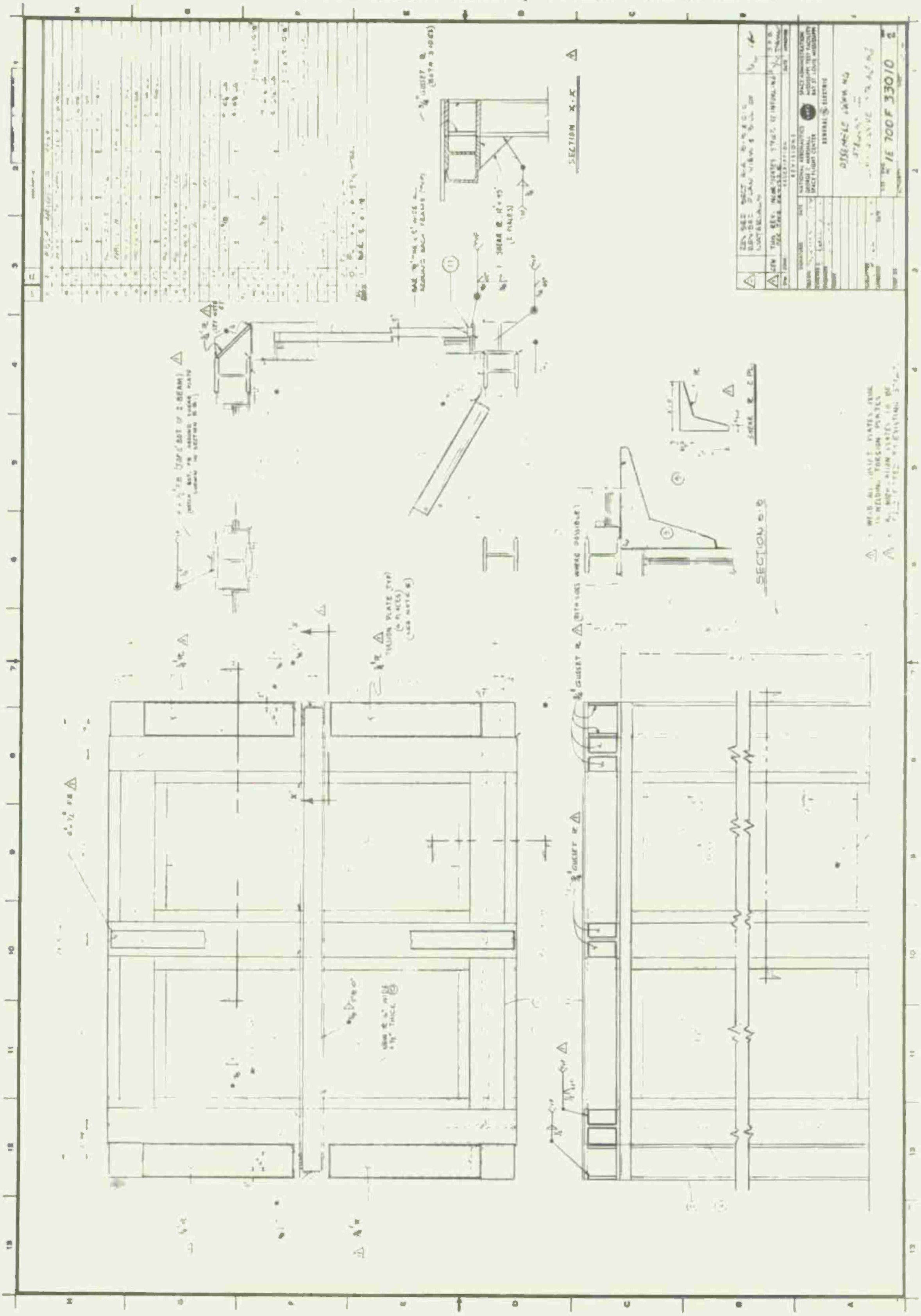

FABRICATION DETAILS
CATEGORY III
SUPPRESSIVE STRUCTURE
1E 700 F 33010

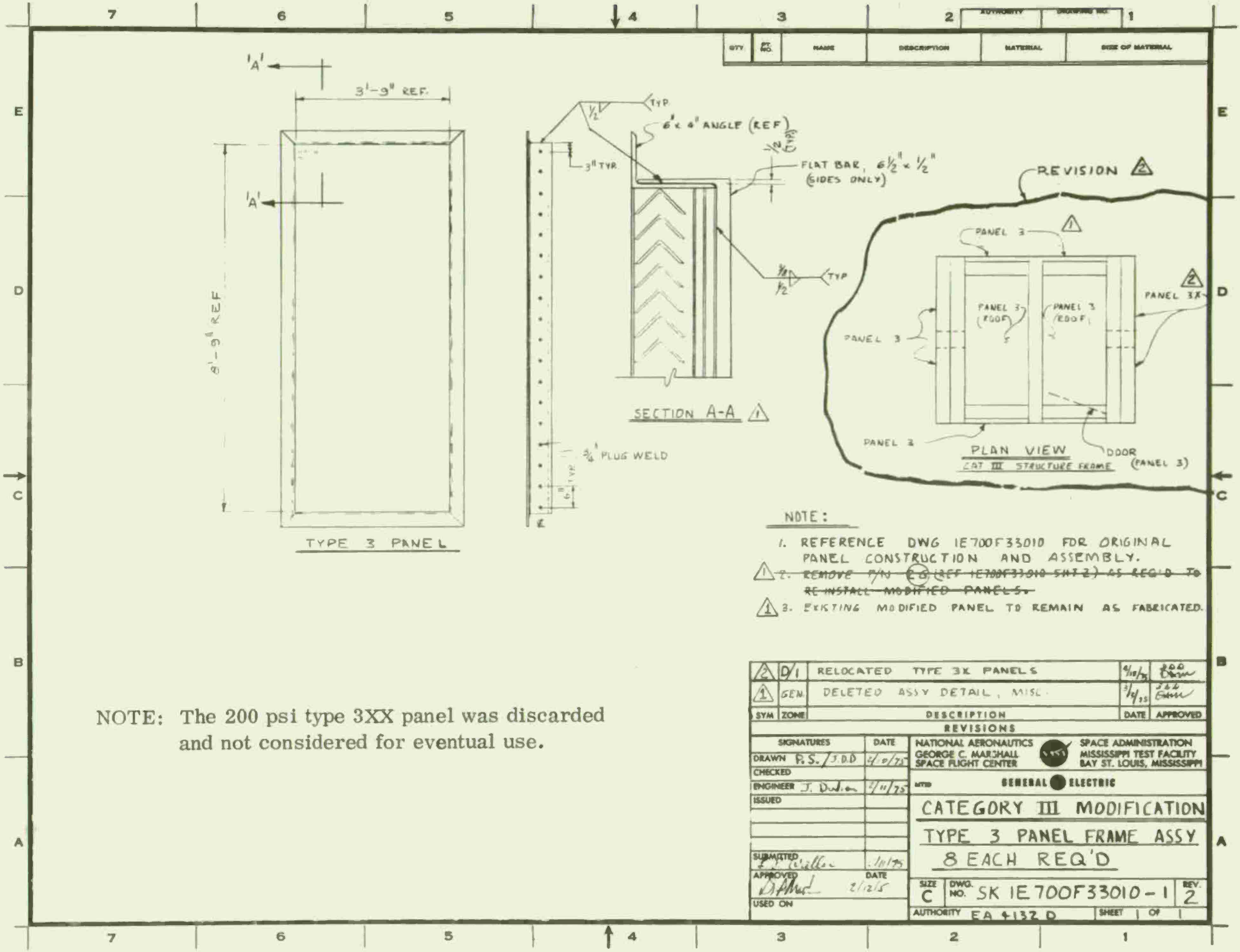
Category 3 Suppressive Shield

Insertion of wall panels into structural frame.

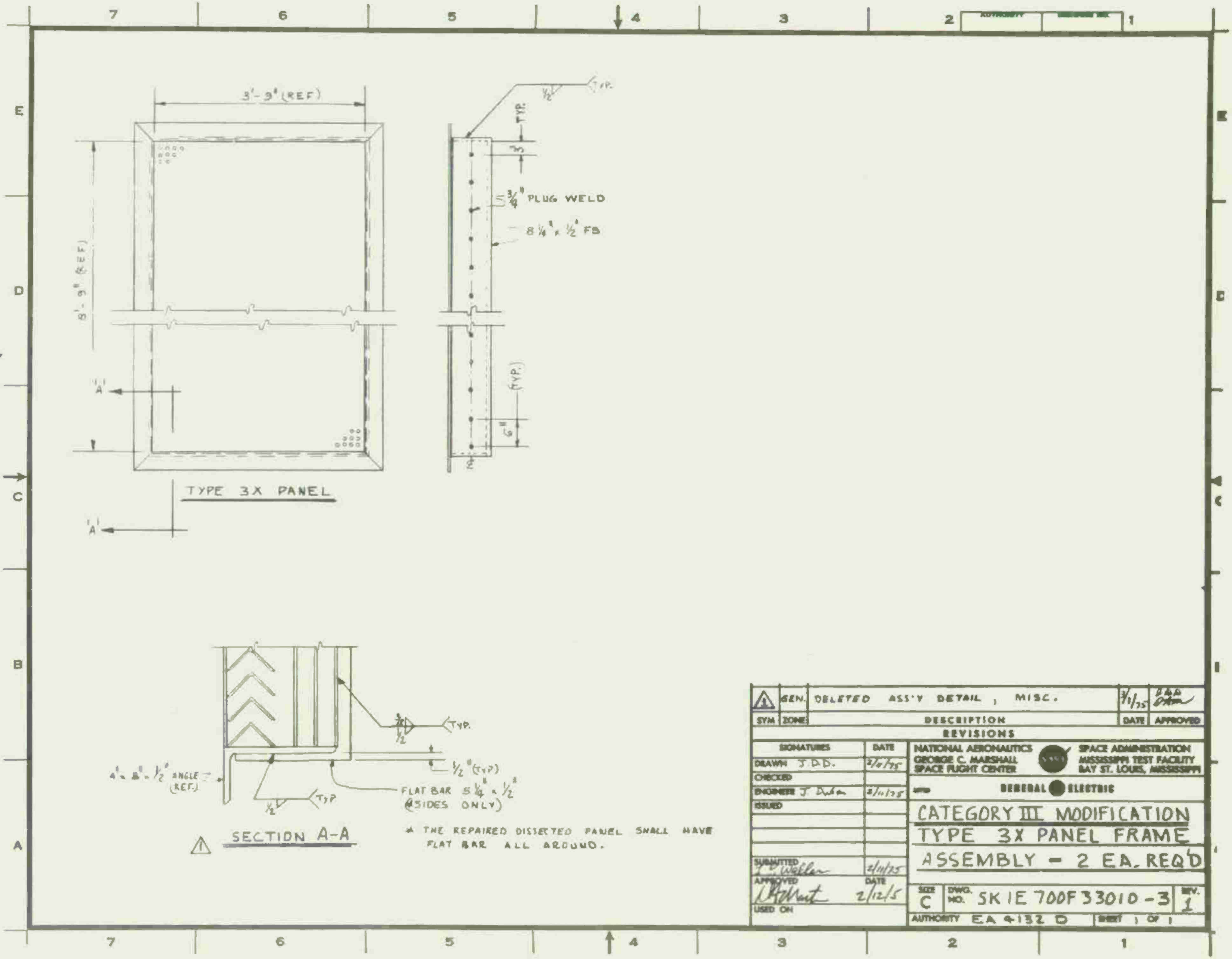
APPENDIX B

CATEGORY 3 SUPPRESSIVE SHIELD, PHASE I MODIFICATIONS






NOTE: The 200 psi type 3XX panel was discarded and not considered for eventual use.

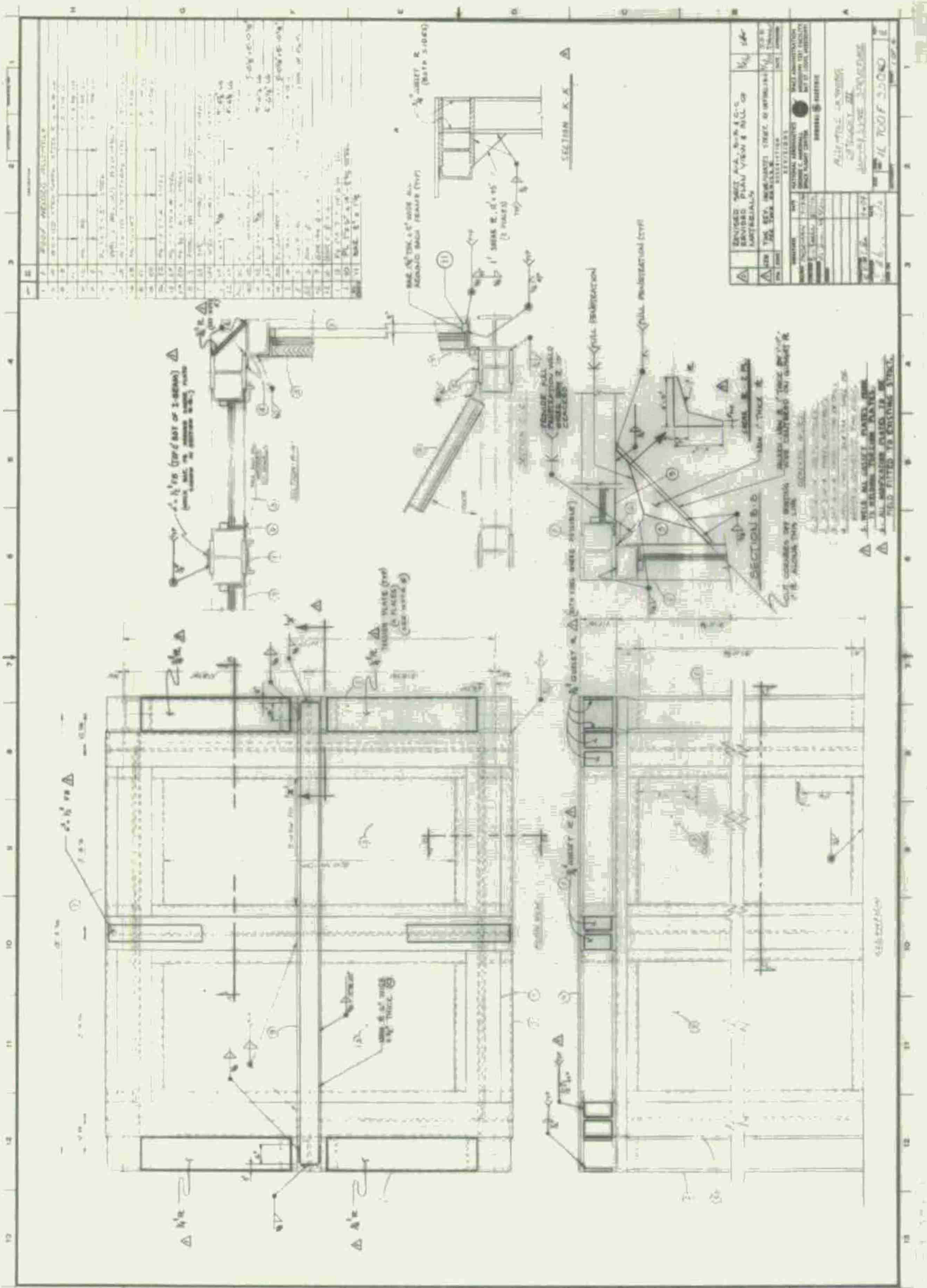


3'-9" (REF)
8'-9" (REF)
TYP.
3"
3/4" PLUG WELD
8 1/4" x 1/2" FB
(TYP.)
6"
'A'
'A'
TYPE 3X PANEL
TYP.
1/2" (TYP)
4" x 8" x 1/2" ANGLE (REF.)
FLAT BAR 5 1/4" x 1/2" (@3 SIDES ONLY)
SECTION A-A
* THE REPAIRED DISSECTED PANEL SHALL HAVE FLAT BAR ALL AROUND.
GEN. DELETED ASS'Y DETAIL, MISC. 3/1/75
SYM ZONE DESCRIPTION DATE APPROVED
REVISIONS
SIGNATURES DATE
DRAWN J.D.D. 2/4/75
CHECKED
ENGINEER 2/11/75
ISSUED
SUBMITTED 2/11/75
APPROVED DATE 2/12/5
USED ON
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MISSISSIPPI TEST FACILITY
BAY ST. LOUIS, MISSISSIPPI
GENERAL ELECTRIC
CATEGORY III MODIFICATION
TYPE 3X PANEL FRAME
ASSEMBLY - 2 EA. REQ'D
SIZE C
DWG. NO. SK IE 700F 33010-3
REV. 1
AUTHORITY EA 4132 D
SHEET 1 OF 1

Category 3 Suppressive Shield

APPENDIX C

CATEGORY 3 SUPPRESSIVE SHIELD, PHASE II MODIFICATIONS



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